CROP YIELDS RESPONSE TO CONSERVATION FARMING AND SPATIAL-TEMPORAL EFFECTS IN ZAMBIA

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CROP YIELDS RESPONSE TO CONSERVATION FARMING AND SPATIAL-TEMPORAL EFFECTS IN ZAMBIA

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We examined crop yields along a wide environmental gradient and spatial dynamics in soil organic matter in response to conservation farming (CF) in Zambia. Maize yields from farmer managed CF and traditional farming (TF) were not significantly different with over 280 on-farm trials with varying soil properties, management practices and environmental covariates. Principle component analysis (PCA) identified inappropriate management practices (planting and insufficient weeding), of which 25% of total variability were major factors restricting CF yields. TF yields were limited by both amount and types of inputs that explained 26 % of total variability.

With addition of different organic and inorganic amendments, average CF yield ranged from 1 to 4 t ha^{-1}, with highest in wetter region (3.4±7.9 t ha^{-1}) and lowest (2.1±6.8 t ha^{-1}) in degraded plateaus. Combined additions of inorganic fertilizer (N-P-K at 200-100-100 kg ha^{-1}) with biochar and manure achieved the highest effect in degraded plateau with yield increase of 320% and 300% respectively as compared to organic matter additions of manure (46%) and gliricidia (24%) in the same region. PCA established pre-existing soil fertility is the major factor in all sites for improved yields and nutrient uptake with organic additions ($P<0.05$). Compost additions (P=0.001), and manure with or without inorganic fertilizer additions (P=0.02) led to greater yields with finer soil texture but not with biochar additions.

Additions of biochar with inorganic fertilizer in wetter region enhanced maize Ca uptake (*P*=0.03) at lower pH (*P*=0.005) and higher rainfall (*P*=0.05).

Total soil organic C (SOC) and N contents were initially 8% and 12% greater in planting basins than in rows over 10-year chronosequence under CF. Both SOC and N contents increased to a greater extent in basins than in rows with increasing years indicating greater SOM accrual. Mineralization of C per unit SOC in basins (R^2=0.83) increased with years under CF indicating an accumulation of more labile SOC, whereas no changes were observed in rows. Potential mineralized N (PMN) increased in both basins (R^2=0.60) and rows (R^2=0.79) although more rapidly in basins than in rows. Greater stability of SOC was observed in areas receiving crop residues only.

BIOGRAPHICAL SKETCH

Lydiah spent her younger days in both peri-urban and rustic areas surrounded by rolling hills landscape of Central and Eastern provinces, Kenya. She graduated with Bachelor of Science Horticulture at Egerton University, Rift Valley province in Kenya. While at Egerton, she was introduced to National Outdoor Leadership School (NOLS) and improved her outdoor and environmental skills. Later she worked with Africa Biodiversity Institute and Women's Rights and Awareness Program on women and land ownership assignments where she increasingly became more aware of loss of biodiversity and the virtues and vices of agriculture as a livelihood. In 2002 after completing an apprenticeship program, she worked as an apprentice instructor and an assistant to Community Supported Agriculture field manager at the Center for Agroecology and Sustainable Food Systems (CASFS), University of California Santa Cruz, USA. These opportunities greatly stimulated her interest in and motivated her to further study on agrobiodiversity conservation.

In 2005, Lydiah earned her Masters in International Agriculture and Rural Development from Cornell University. She then worked for Horticulture department, Cornell University. For her PhD, Lydiah was part of SANREM-CRSP team of faculty and students studying an agricultural markets model for biodiversity conservation in Zambia. Her research was supervised by Johannes Lehmann. She looks forward to putting the skills acquired over time in developing nations.

I lovingly dedicate this dissertation to the Gatere's; parents, sisters, brothers, nephews and nieces who supported me each step of the way; and the patient farmers in Zambia.

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Finally, I will forever be indebted to my family (Parents (Gatere, Njeri), Sisters/Brothers (Nyambura, Arkie, Turi, Muthoni, Ciku, Sybil-Day, Ceri, Turi kanini and Wanyeki); (nephews and nieces Kadi, Gatere, Vickie, Willy, Jaime, Changi, Nyathigi, Njeri, Ethan, Wamoro and Imani) for their patience, encouragement and a great source of inspiration for all those years. Many thanks to Dawit, Brendan, Kirui, Ayesa, Susan, Harriet, Ndiki, Dolapo in any capacity you helped. Dela, my dissertation buddy with whom we explored academic libraries with excellent freebies, we did it!

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CHAPTER 1

CONSERVATION FARMING AS AFFECTED BY ENVIRONMENTAL GRADIENTS AND MANAGEMENT

Abstract

Conservation farming (CF) is an approach implemented to increase food production through integrated soil fertility management and water conservation measures. Despite its wide use globally, conditions under which CF may provide agronomic improvements in Africa are presently under study. To quantify yield benefits of CF, on-farm experiments were conducted on over 280 farms along a broad environmental gradient in Zambia during 2006- 2008, with varying soil properties, management practices and site characteristics that included mean annual precipitation and terrain relief properties. Maize yields from farmer-managed CF and traditional farming (TF) were not significantly different ($P>0.05$). Due to multicollinearity, principal component analysis (PCA) was used to identify whether the biophysical environment (soil properties, climate, relief) or management was more important in restricting crop yields under CF or TF. Yield under CF was more constrained by inappropriate management ($P<0.001$ of multiple stepwise regression; 13% of total variability) such as lack of early planting and insufficient weeding (25% of total variability explained by management) than by environmental properties. In drier regions, basins in CF improved maize yields ($P<0.05$) likely through improved water availability, but in wetter regions, no benefit was observed from improved soil fertility. In contrast, yield under TF varied the most (26% of variability explained by management) with amount and types of inputs. Major issues contributing to the poor performance of CF include the inability to maintain permanent planting basins and the low quality of organic inputs such as manure or composts. The observed management constraints offer opportunities for on-farm improvements but also highlight the complexity of interventions that must go beyond simple increases in farm inputs to make CF a successful farming approach in the region.

Key words: conservation farming, early planting, fertilization, maize, manure, no-till, weeding

1. Introduction

Despite the availability of improved varieties and agronomic practices, the average grain yield of maize in sub-Sahara Africa (SSA) has stagnated around 1-2 t ha^{-1} (FAO, 2010). Soil fertility depletion has been the fundamental biophysical cause of stagnant per capita food production in Africa for the last over 40 years (Sanchez, 2002). A continuous decline in soil nutrient reserves over time across SSA (Smaling et al., 1997) results in continued decline in crop yields that can be either abrupt or gradual depending on soil properties, climate variability, and terrain conditions. Soil properties such as texture, fertility, and organic matter have in general significant effects on maize grain yield (Osmond & Riha, 1996, Rusinamhodzi et al., 2011). To mitigate depletion of soil nutrients, integrated soil fertility management is recommended with the intent to increase food production through strategic integration of new and traditional technologies. These approaches should be tailored to meet variations in soil properties and management conditions to facilitate nutrient restoration.

Superimposed on the inherent variability in soil fertility in agricultural landscapes is the heterogeneity caused by differential resource management by farmers. Management-induced changes in soil properties partially explain yield variability (Jagadamma et al., 2007). Management interacts with and possibly buffers —or alternatively accentuates — the influence of biophysical factors on yield variability. Comparisons of various management effects on soil properties indicate that management influences soil properties and soil variability structure. Subsequent appropriate agronomic practices will positively influence soil fertility restoration. For example, Fatondji (2006) noted the importance of *zaï pit* technology that improved crop yield through nutrient management in planting pits amended with organic and/or inorganic nutrients. Appropriate recommended adoption of agricultural practices can restore and maintain crop productivity and soil quality.

Reversing the trends of soil fertility depletion and soil desiccation presents a significant challenge (Rockström et al., 2009). An initial understanding of spatial variability of soil attributes is essential in characterizing complex relationships between soil properties and environmental factors (DeGloria, 1993; Goovaerts, 1998) as well as in determining appropriate soil resource management practices (Bouma et al., 1999). Furthermore, spatial variability in soils exists at many scales with different and dominant controlling factors. Soil physical and chemical properties vary according to slope position (Ovalles & Collins, 1986; Miller et al., 1988). Slope gradient and elevation affect soil nutrients through soil erosion and deposition (Qiu et al., 2001a; Tan et al., 2004), while slope aspect and slope gradient can control movement of water and material and contribute to the spatial differences of soil properties. As a result, a combination of soil properties and topographic features can explain 60% or more yield variability (Kravchenko and Bullock, 2000). The effects of these variables become potentially more important within regions where climatic variation is not distinct. According to Bationo et al. (2006), different dominant soils within agroecological zones of SSA demonstrate distinct trends in moisture and nutrient storage capacity, organic matter content and nutrient depletion. Therefore, before promoting CF on a large scale, it is imperative to conduct rigorous and extensive field trials tailored to optimize CF practices under a wide variety of environmental conditions.

Conservation Agriculture

Conservation Agriculture (CA) has been defined by FAO (2010) by three linked principles namely; (i) continuous minimum mechanical soil disturbance (ii) permanent organic soil cover, and (iii) diversification of crop species grown in sequences and/or associations. Conservation agriculture has been proposed as a widely applicable set of management principles that address the problems of soil degradation resulting from agricultural practices that deplete organic matter and nutrient content (Stoorvogel and Smaling, 1998; Giller et al., 2009, Govaerts, 2009; Verhulst et al., 2010). Conservation agriculture practices offer the potential to increase maize productivity (Govaerts et al., 2007) by increasing soil organic carbon (Lal et al., 2007). Conservation agriculture has also been shown to increase efficient use of rainwater through increased water infiltration (Thierfelder and Wall, 2009) thereby ensuring higher and more stable yields in adverse environmental conditions such as low nutrient and water availability (Erenstein, 2002, 2003). However, the techniques to apply the principles of CA will vary in different situations, and will be different with biophysical and system management conditions and farmer circumstances (Verhulst et al., 2010).

In Africa, CA is viewed as a technology that can help improve food security and mitigate drought effects. Farmers often receive packages of seeds, fertilizer and lime free or on credit as an incentive to adopt CA (Haggblade and Tembo, 2003; Twomlow et al., 2008a;). Consequently, CA is perceived as a technology targeting vulnerable households (Twomlow et al., 2008b; FAO, 2011) and as a way of mitigating the effects of food insecurity and chronic poverty. In addition, unbiased quantitative assessments of on-farm smallholder CA yield improvements are largely lacking in Southern Africa and are available from on-station, demonstration farms and researcher-managed trials (Giller et al., 2009; Erenstein et al., 2012). A blind transfer of CA technology from South America where it originated without consideration of specific, local management and soil conditions explains much of the perceived failure of CA in Africa (Giller et al., 2009) especially where farmers provide their own supplies. Providing site-adapted management adaptation will help advance what some see as a promising management approach (Hobbs et al., 2008; Twomlow et al., 2008a; Erenstein et al, 2012). Specifically, under what soil and climate conditions CA works is only supported by limited data (Johansen et al., 2012) and needs more research. Understanding relationships that determine this variability is limited and estimation of yield in response to changing environmental conditions remains problematic. In complex landscape management systems such as in SSA, yield differences can be attributed to variability in soil properties, climatic conditions, topographic features, and management.

Conservation farming practice

Conservation farming (CF) is a CA package promoted in Zambia for smallholder farmers utilizing small farm implements such as hand-hoes to create planting stations (Hove and Twomlow, 2007, Mazvimavi and Twomlow, 2009) and lately animal powered rippers. Hand-hoe CF as applied in Zambia is an aggregate of best-recommended management practices extended from previous field research in Zimbabwe (Oldreive, 1993). Zambian extension service disseminated CF practices that have been practiced since the mid-80s (Haggblade et al., 2003). The principles include: (i) completion of land preparation in the dry-season using minimum tillage systems; (ii) no burning but retention of crop residues with recommendation of 30 % minimum cover; (iii) establishment of precise and permanent (or fixed) planting stations (basins or potholes); (iv) early and continuous weeding of four to five times or application of herbicide; and (v) crop rotations including 30% nitrogen-fixing plants (CFU, 2003). For hand-hoe farmers, dry-season preparation of a precise grid of permanent basins (15,850 basins per hectare) is recommended for precise application and concentration of soil organic and inorganic amendments and lime, and timely dry planting before the onset of rainfall (Haggblade and Tembo, 2003). Unlike the conventional hand-hoe and ploughing technologies they replace, CF disturbs only about 15% of the soil where crops are planted. The guidelines for CF hand-hoe practices (CFU, 2003a & b) include annual digging of basins (0.3 m by 0.15 m by 0.15 m) using a chaka hoe (a wide-bladed specialized and modified from traditional hoe to sharpen itself as it digs) after the harvesting period. Basins are crucial and emphasized for water harvesting along the environmental gradient and for breaking the plough pan for newly converted CF fields. Application of organic and inorganic fertilizers in each basin of 0.15m depth is advocated as they complement each other and amendments covered with a thin layer of soil before the onset of rainfall. Seeds are planted at the appropriate seeding rate in rows with a distance of 0.9 m between rows and 0.7 m within each row. Weeding with a hand-hoe or herbicide application throughout the cropping season is encouraged to reduce soil disturbance, and the last weeding before crop harvesting is critical to reduce generation of weed seed. Crop residues are retained and in case of low quantities of residues produced *in situ*, farmers are encouraged to use locally available grass. In contrast, the traditional *chitemene* system of shifting cultivation (Stromgaard, 1984) and *fundikila* system of grass mound (Stromgaard, 1990) (hereafter called traditional farming, TF), is characterized by a short cropping period followed by long fallow periods (Mansfield, 1975; Chidumayo, 1996). However, due to population pressure available land for this practice is diminishing. Current TF practices include shorter fallow periods or none at all (Matthews et al., 1992), continuous and intensive soil preparation (ploughing) with hand-hoe or animal pulled plows and planting after the second heaviest rainfall combined with burning of crop residues or communal free post-harvest grazing of livestock which is customary. Planting furrows are made with a hoe after ploughing. Depending on availability, little or no inorganic soil amendments are applied after ploughing and during planting. Organic soil amendment like animal manure is reserved for vegetable production during the winter season. Seeding rate and spacing depends on the variety selection and farmers preference. However, recommended planting space between rows is a distance of 0.7 to 1 m and 0.15 to 0.3 m within each row. Weeding is generally done manually once during the cropping season due to labor constraints.

To investigate the complicated interactions between environmental co-variates and management practices, simple correlation and multiple regression analyses were used to model relationships between crop yield and environmental variables. However, multiple regression analysis of inter-correlated soil properties and site characteristics (hereafter-environmental co-variates) can result in multicollinearity when attempting to identify environmental co-variates that determine yield differences in agricultural slope positions (Bowerman and O’Connell, 1990). Choosing appropriate statistical tools is an important step. Grouping strongly correlated properties for multivariate analysis techniques avoids multicollinearity problems. Principal component analysis (PCA), a multivariate method, aims at data reduction through linear combinations of the original variables to a few independent variables that explain most of variance from a large data set (Martens and Naes, 1989). Identifying the most sensitive soil and/or topographic properties influencing crop production therefore requires multivariate statistics tools (Mallarino et al., 1999a; Jiang and Thelen, 2004; Kaspar et al., 2004; Blanco-Canqui et al., 2006; Cox et al., 2006).

The primary goal of this study was to quantify potential benefits of CF on yield, a CA practice of creating planting basins in the dry season and compared to traditional farming (TF), a practice of land preparation after the onset of rainfall both systems practiced by smallholder farmers using small farm implements such as the hand-hoe. Yield differences between CF and TF were quantified in a sub-humid tropical miombo woodlands in the Luangwa watershed, Zambia. Effects of mean annual precipitation (MAP), percent clay, and slope position on yields were determined. We hypothesized that CF increases crop yields compared to TF especially under extreme adverse environmental conditions of low soil moisture and low nitrogen and phosphorus availability. Our specific objectives were to (i) elucidate the relationships between crop yields, soil properties and site characteristics of TF compared to CF; (ii) examine the effects of soil and site variables on crop yields of TF compared to CF; and (iii) investigate whether environmental conditions or management practices influence the success of CF to a greater extent in improving crop productivity.

2. Materials and methods

2.1. Study site description

The experimental sites were located in Lundazi, Mambwe and Mpika districts of Eastern and Northern provinces in Zambia within Universal Transverse Mercator projection (UTM) Zone 36S (11^0 51′ S to 13^0 30′ S latitude, 31^0 25′ E to 33^0 007′ E longitude). The terrain elevation ranged from 500 to 1400 m above sea level with mean annual temperatures ranging between 10 and 35°C (Table 1). Mean annual precipitation lies between 500 to 1250 mm with a unimodal distribution pattern from

November to April. The area was chosen on a physiographic basis and is subdivided into three agroecological zones (AEZ) (Chiwele and McKenzie, 1996) differentiated by rainfall pattern (Figure 1) and soil type (Table 2). The land cover is extremely heterogeneous due to a variety of adjacent topographic features with natural lands mixed with crop cultivations and cultivated areas alternating with non-cultivated areas (Figure 1). Over 280 smallholder farmers with less than two hectares of land and practicing both conservation and traditional farming were selected (for locations, see supplementary information) from the three AEZs. Sites were stratified according to mean annual precipitation, slope position and soil texture to ensure representation of the most important environmental characteristics.

In AEZ I soils have a higher pH and nutrient content than in other AEZs (Table 2) and are classified as Haplic Luvisols (FAO, 1973) in the Rift troughs and Haplic Solonetz (loamy and clayey soils with coarse to fine loam top soils) on flat land. The rainfall in this zone is early, erratic and low with a cumulative average of 796 mm during the cropping season (Figure 2). AEZ II is a degraded plateau with moderately leached clayey to sandy-loam soils classified as Haplic Luvisols, Haplic Acrisols and Haplic Lixisols, with an average cumulative rainfall of 900 mm. Soils in this zone have coarser texture, lower nutrient and carbon (C) contents than the other two AEZs (Table 2). Soils in AEZ III are highly weathered and leached with clayey to loamy textures, and are classified as Haplic Acrisols, having low pH and CEC (Table 3) indicative of a mineralogy dominated by highly weathered clays. AEZ III has the greatest cumulative rainfall with 1045 mm, which starts later and has more even rainfall distribution (Figure 2).

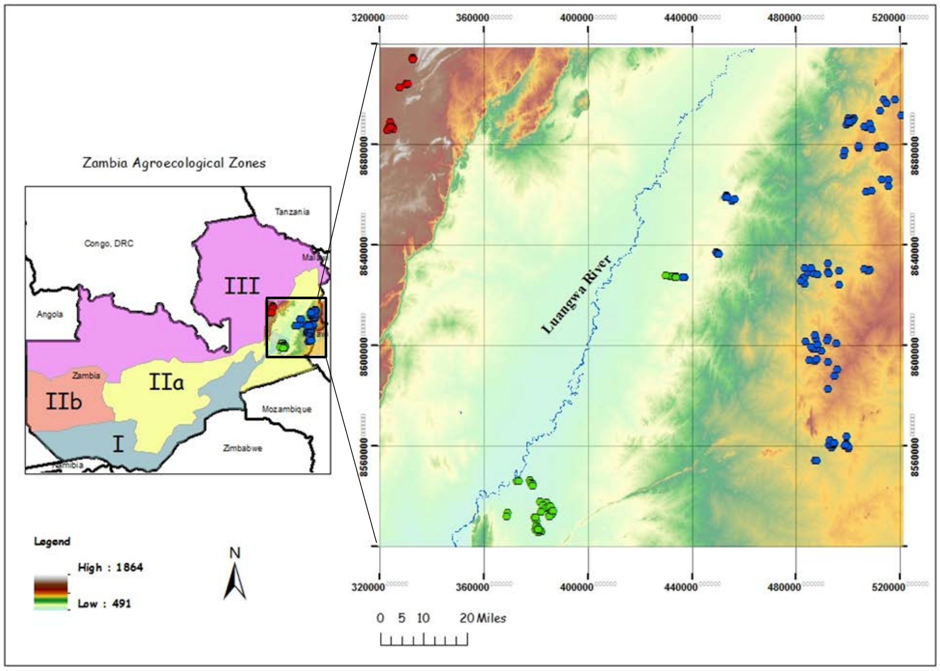

Figure 1.1. Topographic overview of the study area and the farm locations.

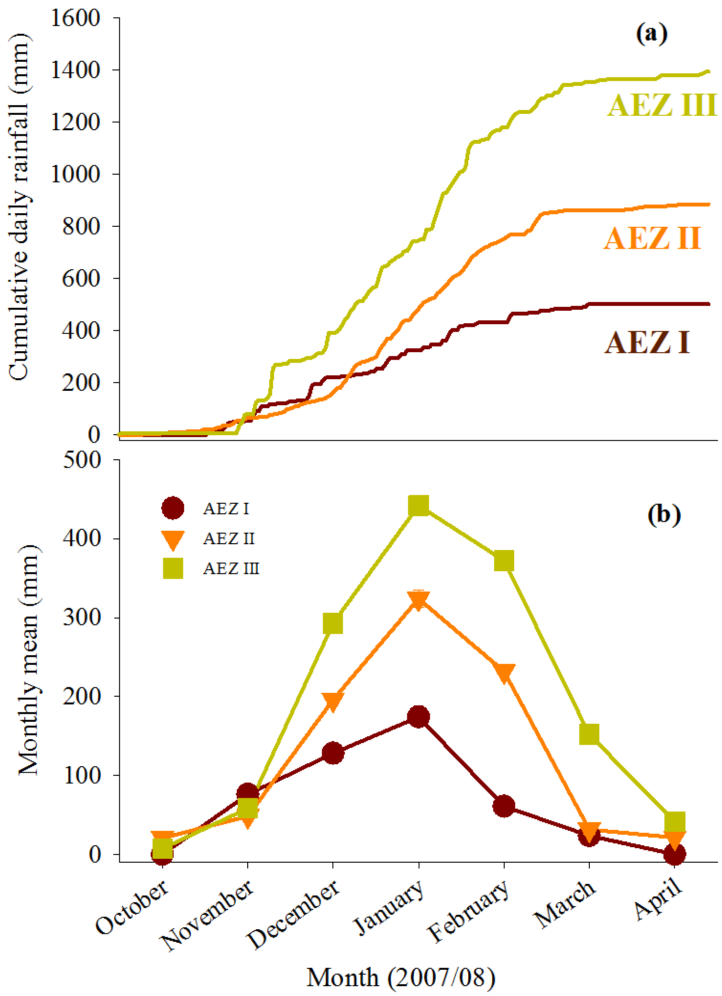

Figure 1.2. (a) Cumulative daily rainfall recorded by farmers throughout the rainy season 2007/2008 (means and standard deviations; n=92, 156, 32 for AEZ I, II, III, respectively); and (b) average monthly rainfall (means and standard deviations).

2.2 Experimental design and methods

Farms were identified in areas with a wide variability of rainfall gradient, terrain and soil texture that practiced (in close proximity within 100 m distance) both TF and CF. Soil texture and terrain variables were comparable across the rainfall gradient, but significantly varied within each AEZ (Table 3). The experimental design was stratified random sampling with repeated measures and treatments assigned at farm level. Stratification was implemented based on a three-level model to examine the effects of environmental variables. To ensure equal representation, 45 strata were defined based on (i) mean annual precipitation (MAP) (three AEZs); (ii) five slope positions and (iii) soil texture (fine, moderate and coarse clay content). Within each stratum, six farms with two treatments (TF and CF) were randomly chosen and repeated harvest measurements taken on each treatment.

Crop production of maize was managed and practiced by farmers, and researchers quantified only yield and soil properties. The CF plots were established on existing one-year-old CF fields with maize as a previous crop while TF fields were located on adjacent fields by the same farmer with the same cropping history prior to CF establishment. In addition to these researcher-identified plots, which were demarcated before the cropping season and maintained over two years, one additional plot of CF and TF was randomly selected on each farm at harvesting. The researchers used the additional pair of plots to verify whether assignment of plots prior to the cropping season introduced an artifact through different farmer management practices. Farmers may unintentionally or intentionally change their practices depending on their perception of expected outcomes of a trial (Boughton, et al., 1990). The trials were conducted during the rainy seasons of 2006/2007 and 2007/2008, but only the last season is presented here. Plots had a dimension of 4.5 m by 3.5 m.

2.3. Field trial management

Farmers managed the fields according to the practices established for CF in comparison to TF. The CF practices followed the instructions given by extension agencies and were not reinforced by the researchers. Actual management practices were recorded for every CF and TF site, which included variety of maize planted, dates of planting, previous crops planted (rotation), harvesting and dates of weeding, as well as the type and amount of soil amendments (fertilizer, lime, compost, manure) and date applied. The design and position of the basins were not assessed separately. The size of the basin differed depending on the type of hoe used, farmer practice and the time when the basins were dug. The choice of maize variety for planting was made by farmers in order to measure CF yields in comparison to TF yields. Maize was planted using four seeds per planting hole in CF and thinned to three (Aagaard and Gibson, 2003a, 2003b) at a rate of 20-25kgs of seeds per hectare while TF recommended seeding rate was 20-30 kgs of seeds per hectare. However, seeding rate and spacing depends on the variety selection and farmers preference and is planted in furrows. Farmers supplied their own resources currently available to them, for instance soil organic and inorganic inputs.

2.4. Plot sampling and analyses

Maize grain and stover yields were determined in all plots at harvest at physiological maturity. Stover and grain yield were measured on subplots of 4.5 m by 3.5 m. To avoid edge effects a net harvest area of 5.7 m^2 was established within the TF and CF plot area. The net harvest area was based on equivalent to leaving one row (0.9 m) and one plant at the end of each row (0.7 m) in CF plot and the same measuring standards of leaving 0.9 m and 0.7 m was applied for TF. Fresh plant materials were weighed and a representative subsample dried at 60°C for 48-72 hours and then re-weighed. An aliquot grain subsample of about 500 g was taken for moisture content determination using a PreAgro grain moisture tester (PreAgro 35 Oy Santasalo-Sohlberg, AB; Finland) in order to check whether grain had attained 13% moisture content after which yield measurements were corrected to a moisture content of 15.5%. In less than 4% of the cases where cobs were missing from the subplot (removed by people or destroyed by elephants), the average weight of the grain per harvested cob was multiplied by the measured plant density at harvest to obtain an estimate of the grain yield. Each maize plant was assumed to have one ear based on majority observations and individual average cob weight corrected irrespective of human removal or animal destruction. The geographic coordinates of the sampling points were taken and recorded with a handheld global positioning system (GPS; Garmin 72XL model, instrument precision of ±10 ft) using Universal Transverse Mercator (UTM, Zone 36) (for locations see supplementary information).

2.5. Field sample collection and laboratory analyses

For site characterization, farmers recorded actual rainfall daily during the cropping season using a rain gauge on each farm. Ten random topsoil samples from both CF and TF plots on each farm were taken at a depth of 0.15 m and pooled as a composite before implementation of the treatments. Sub-samples from the bulked composite were air dried and passed through a 2-mm sieve. The samples were analyzed for pH (in KCl) at the w/v ratio of 1:2.5 using a glass electrode. Mehlich 3 soil extracts (Anderson and Ingram, 1993) were analyzed for available Ca, Mg, K, and P by Inductively Coupled Plasma Atomic Emission Mass spectrometry (ICP-MAS, Spectro Ciros, Spectro A.I. Inc. MA, USA).

To estimate cation retention independent of soil pH, potential cation exchange capacity (CEC_{pot}) was determined by quantifying NH_4 exchanged with 2 N KCl after saturating cation exchange sites with NH_4 acetate buffered at pH 7.0 (Anderson and Ingram, 1993; Hendershot et al., 1993), followed by colorimetric NH_4 analysis on a continuous flow analyzer (Technicon Auto Analyzer, Colorimeter; Technicon, NY, USA). Total soil C and N were determined by dry combustion. A subsample of 0.5 g of each soil sample was finely ground for 10 min with a ball mill (Retsch® MM301, Retsch Inc, Newton PA, USA). From the fine material a 20-mg sample was weighed into Sn capsules and analyzed for total C and N contents with a Europa ANCA-GSL CN auto-analyzer (PDZ Europa Ltd., Sandbach, UK).

2.6. Terrain parameters

Digital elevation models (DEM) produced from the Shuttle Radar Topographic Mission (SRTM; CGIAR-CSI) at 90-m resolution were used to derive slope gradient, slope aspect (direction of slope), slope position and slope curvatures (profile, plan, absolute) for each field plot area. Geographic coordinates and elevation values were taken and recorded using a Garmin 72XL GPS instrument when visiting each plot. Elevation values were significantly correlated (R^2= 0.99; $P<0.0001$) between SRTM DEM (m) at 90 m resolution and GPS recorded elevation (m) along the environmental gradient.

The SRTM-derived terrain parameters were computed using ArcGIS 9.3 using a standard 3 x 3-raster (or grid cell) neighborhood size of 90 by 90 m pixels. Slope gradient in arc-degrees was derived using the Spatial Analyst surface tool in ArcGIS (ESRI, Redlands, CA). This process uses a 3 x 3 raster neighborhood around the processing or center cell to calculate slope gradient values. The algorithm identifies the maximum rate of change in elevation value from each cell to its neighbors, defined as the first-order derivative of the terrain (ESRI, 1996).

Topographic Position Index (TPI), the difference between the elevation at a cell and the average elevation in a neighborhood surrounding that cell, was calculated using topographic arc tools (Jenness, 2010). TPI was utilized to classify the slope position within each AEZ into slope position classes based on extreme TPI values and by the slope gradient. High TPI values are found near hilltops while low TPI values in valley bottoms and values near zero are either on flat ground or in mid slope positions. In order to classify small features like streams and drainages, a small rectangular neighborhood was used. In this study, five slope positions were derived and coded. Slope curvature (absolute, profile and plan) was derived using Spatial Analyst surface tool in Arc GIS (ESRI, Redlands, CA) and calculated using a 3 by 3 raster neighborhood. The values were reclassed to concave or convex based on positive or negative values (if $n>0.1$, $-0.1>n<0.1$, $n<-0.1$). Zero values have no slope curvature. Curvature describes the acceleration or deceleration of water flow over a surface. For instance, in plan curvature negative curvature (if $n<-0.1$) corresponds to concave surfaces and flowing water tend to converge, while positive curvature (if $n>0.1$) corresponds to convex surfaces or hills and flowing water will tend to diverge, and vice versa for profile curvature positive and negative values. Here we use the value of absolute curvature which integrates profile and plan curvatures. Slope aspect (azimuth) was computed in units of arc-degrees, recoded through the cosine function from north, and classified into four degree categories: -1 represent south (135-225); -0.5 represents west (225-315); 0.5 east (45-135); and 0 north (315-450) after cosine transformation. Table 1 shows the elevation and slope data for the region. For quantitative validation of the DEM terrain parameters, a value was calculated for the center of each plot based on four GPS coordinates at the corners of each plot (Figure 1).

2.7. Statistical methods

Statistical analysis was conducted using three level models since plots were nested within farms and repeated measures over time. Analysis of variance (ANOVA) was conducted using JMP (SAS Institute Inc.; Cary, NC) to test the null hypothesis of expected higher grain yields under CF than TF. Treatment means were separated using standard error of difference. The soil chemical and physical properties and sites characteristics were used as environmental co-variates. Important management practices were correlated with yields. Correlation analyses were conducted to determine if any linear relationships existed between the co-variates and main effects as well as the interaction effects. A principal component analysis (PCA) was conducted using JMP (SAS Institute Inc.; Cary, NC) to investigate the site characteristics and identify important soil and management practices to be used as inputs for further analyses.

Table 1.1. Summary statistics of elevation, slope gradient, mean annual temperature and precipitation.

Site characteristics	Mean	Max.	Min.	SD‡	Range
Elevation, m a.s.l.	921.4	1427	533	300.07	894
Slope gradient, degrees†	1.28	4.72	0	1.02	4.72
MAP, mm*	795.6	1398.7	490	258.39	908.7
MAT, °C*	20.6	34.8	10.1	n/a	24.7

Source: *Lusaka Meteorological station; †SRTM-DEM from CGIAR-CSI; ‡ SD Standard deviation; MAT Mean annual temperature: MAP Mean annual precipitation

Groups of soil properties, site characteristics and management practices of factors derived from PCA are considered mutually orthogonal, uncorrelated and successively explain the maximum residual variation (Sena et al., 2002). A factor, as an array variable, may hold contribution from all 13 soil properties, 7 site characteristics or 11 management practices. Total variance of each factor was defined as eigenvalue (Swan and Sandilands, 1995) and factors with an eigenvalue ≥ 1 (Kaiser's criterion) (Kaiser, 1960; Brejda et al., 2000) and those that explained at least 5 % of the variation in the data (Wander and Bollero, 1999) were retained for further analyses. Environmental co-variates and management practices in each retained PC were analyzed and selected empirically based on their loading coefficients. Generally, environmental co-variates with higher loading coefficients were included in each factor because they could be expected to have greater effect on yield variability. However, there are no established or unambiguous rules to help decide what a 'large' factor loading is (Mallarino et al., 1999b). Environmental co-variates and management practices with factor loadings >0.60 were selected to be included in each factor. If the loading coefficient was >0.60 in more than one factor, it was included in the factor having the highest coefficient value for that property. The retained factors were subjected to varimax (maximum rotation) rotation to redistribute the variance of significant factors and thereby maximize the relationships (SAS Institute, 1994). Highly weighted variables within a factor were considered important and retained in the data set. Correlation coefficients were calculated among the selected soil variables, site characteristics and management variables on crop yield. Lastly, stepwise regression was employed to analyze the combined effect of all-spatial and management characteristics on crop yield. To study the relationship between environmental and management practices, multiple regression analysis was performed using derived PCs as independent variables and average grain yield as dependent variable at $P \leq 0.05$. Finally, stepwise multiple regression analysis was performed for selecting the optimum subset of soil, terrain variables and management practices for predicting grain yield.

3. Results

3.1. Average maize yields

Average grain yields varied from 0.9 to 1.6 t ha^{-1} (P=NS) in all three AEZs (Table 2). Similarly, harvest index in all three zones were not significantly different (P>0.05). There was no significant (P>0.05) increase in yield observed in farmer-managed and practiced conservation farming (CF) over farmer-managed and practiced traditional farming (TF). There were no significant (P>0.05) yield differences found between random and pre-allocated plots, confirming validity of comparisons between treatments.

Table 1.2. Maize yield and fresh harvest index under either traditional (TF) or conservation farming (CF) during 2007/08 cropping season.

	Grain yield (ton ha^{-1})				Fresh Harvest index		
Farming System	AEZ I	AEZ II	AEZ III	All Sites	AEZ I	AEZ II	AEZ III
TF	1.3 (0.04)	1.0 (0.04)	1.6 (0.11)	1.2 (0.04) a	0.32 (0.02)	0.38 (0.01)	0.45 (0.03)
TF Random	1.4 (0.11)	0.9 (0.03)	1.2 (0.05)	1.2 (0.07) a	0.29 (0.02)	0.33 (0.02)	0.3 (0.02)
CF	1.5 (0.07)	1.0 (0.04)	1.4 (0.09)	1.2 (0.04) a	0.38 (0.01)	0.4 (0.01)	0.49 (0.03)
CF Random	1.4 (0.07)	1.2 (0.07)	n/a	1.2 (0.07) a	0.32 (0.02)	0.32 (0.02)	n/a
LSD (0.05)	0.08	0.31	0.21	0.14	<0.0001	0.78	0.02
P value (random)	0.4	0.72	0.51	0.22	0.21	0.07	n/a
Observations (n)‡	83	165	32	162, 99, 86	92	156	32

Standard error of the mean in brackets; n/a, this comparison was not available in AEZ III; Comparison is done for all treatments in all sites, same letter indicates no significant difference between treatments; ‡ comparison between n=162 is CF and TF, n=99 is TF and TF Random, n=86 is CF and CF Random.

3.2. Relationship between soil properties and yields

Univariate analysis of individual soil properties (Figure 3 & 4) did not correlate strongly with crop yields. Only total C and N showed correlation coefficients above 0.2 ($P<0.001$) (Figure 3). Due to multicollinearity among soil properties, principal component analysis (PCA) was performed using the 15 soil properties selected to group the correlated soil properties to the smallest possible subsets representing the majority of variation. PCA identified four principal components (PCs) with eigenvalue >1 which were retained to better quantify relationships among soil variables and yield. These PCs cumulatively explained 75% of the total sample variance, suggesting that four PCs adequately explain the variation in the soil (Table 4). However, these components only explained 11.3% of the soil variability (sum of variance explained in Table 4; sum of all soil variance is 15.1%). The first, second, third and fourth PC had variances (equal to the largest eigenvalue) of 6.9, 2.01, 1.37 and 1.02 accounting for 33%, 23%, 11% and 8% of the total variation of soil properties, respectively. The first and most important PC (PC1) had high factor loading (>0.90) for properties such as finer soil texture, total soil C and total soil N, available Ca, Mg and Mn. PC2 had high loading from CEC, available Na, K, S and Fe and collectively explained 23% of the sample variance. Available Cu and P dominated PC3 while soil pH and available Zn dominated PC4.

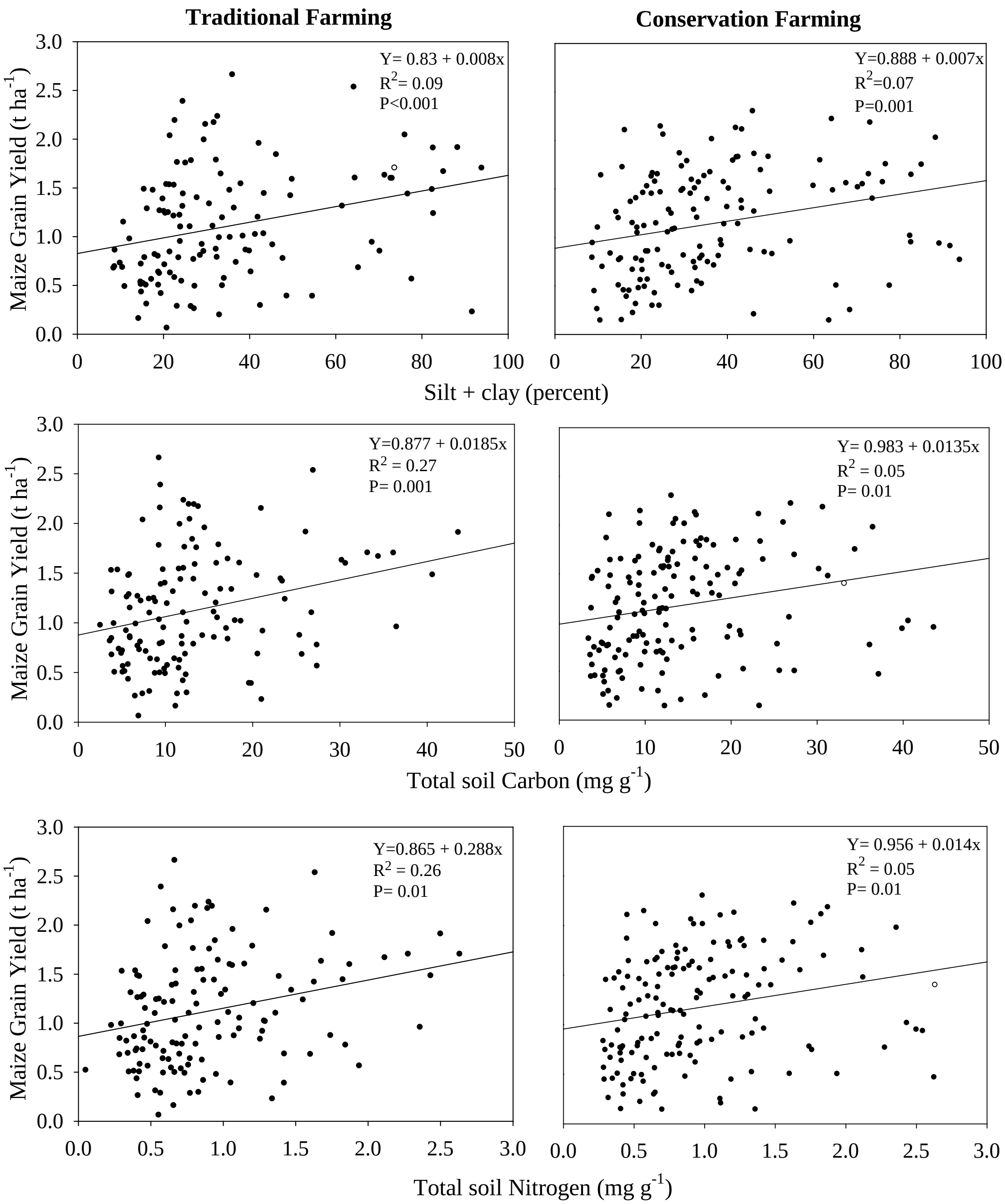

Figure 1.3. Relationship between select soil properties and yields under traditional and conservation farming in Zambia (n=280).

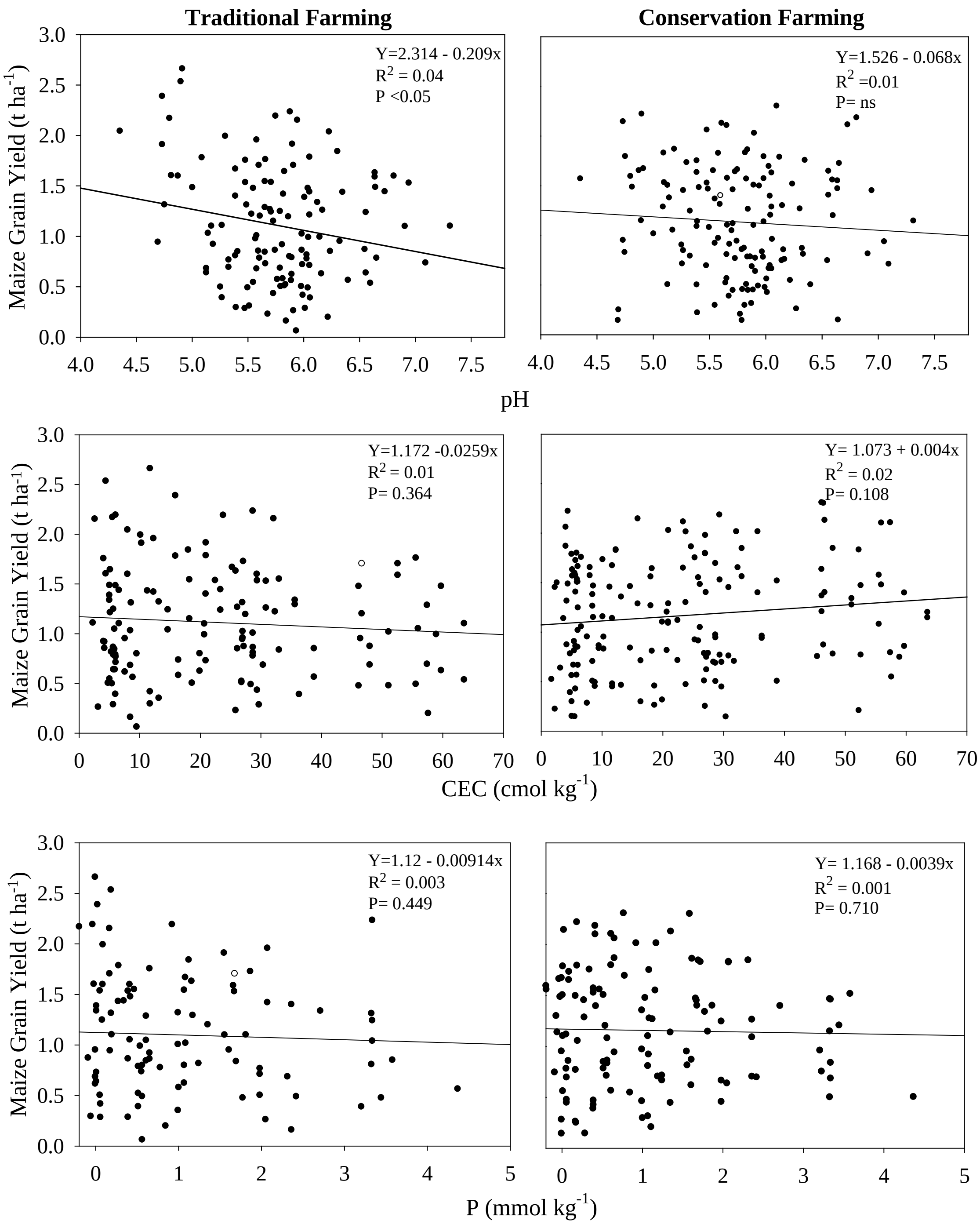

Figure 1.4. Relationship between select soil properties and yields under traditional and conservation farming in Zambia (n=280).

Table 1.3. Soil physical and chemical properties across the three AEZs.

	AEZ I			AEZ II			AEZ III		
Soil properties	Mean	SD†	CV‡	Mean	SD	CV	Mean	SD	CV
Silt + clay, %	47.8	22.3	46.7	23.7	9.1	38.5	52.6	20.8	39.6
pH (KCl)	6.0	0.5	7.7	5.8	0.5	7.8	5.0	0.4	8.5
Total C mg g^{-1}	18.5	8.8	47.3	8.9	4.6	51.8	17.9	9.7	54.3
Total N mg g^{-1}	1.3	0.6	42.7	0.6	0.3	43.8	1.1	0.5	48.2
CEC, $mmol_c$ kg^{-1}	318.3	157.0	493.2	187.3	162.0	864.8	101.8	65.2	639.9
Available P, mg kg^{-1}	21.4	10.9	196.0	14.4	6.3	230.0	21.4	27.7	77.0
Ca, $mmol_c$ kg^{-1}	22.5	9.3	41.5	7.4	5.6	75.9	9.0	5.0	55.3
Mg, $mmol_c$ kg^{-1}	8.1	5.9	72.4	1.9	3.9	206.2	3.0	1.4	45.6
K, $mmol_c$ kg^{-1}	2.6	4.4	169.6	0.9	4.0	469.6	0.3	0.3	72.7
Na, $mmol_c$ kg^{-1}	1.0	4.6	441.0	0.5	4.1	788.5	0.1	0.1	85.6
Fe, mg kg^{-1}	73.8	24.6	33.4	32.8	9.9	30.2	28.5	8.4	29.6
Zn, mg kg^{-1}	4.36	3.9	1.11	4.02	3.9	1.04	7.36	6.6	1.11
Mn, mg kg^{-1}	1.5	4.5	296.3	0.7	4.4	605.3	1.2	0.9	72.6
Cu, mg kg^{-1}	52.9	18.7	35.3	55.4	25.2	45.5	36.9	17.6	47.7
S, mg kg^{-1}	9.5	7.4	77.5	2.8	5.0	182.3	1.6	3.8	238.2

CEC, potential cation exchange capacity; ‡CV, coefficient of variation; †SD, standard deviation

Table 1.4. Variable loading coefficients in the first four principal components (PCs) in all sites and their individual and cumulative variance and eigenvalues.

Soil properties	PC1	PC2	PC3	PC4
Percent silt +clay	**0.916**	0.122	-0.016	-0.072
pH	-0.008	0.265	0.241	**0.787** [a]
N	**0.918**	0.228	0.029	0.022
C	**0.929** [a]	0.123	-0.039	0.001
CEC	-0.001	**0.744**	0.035	0.103
Ca	**0.785**	0.446	0.100	0.188
P	-0.036	0.127	**0.755**	-0.122
Mg	**0.791**	0.457	0.194	0.101
K	0.510	**0.668**	0.335	0.079
Na	0.476	**0.769**	0.101	-0.006
Fe	0.422	**0.742**	0.121	0.006
Zn	0.078	0.138	0.423	**-0.649**
Mn	**0.714**	0.094	-0.007	-0.240
Cu	0.072	0.030	**0.798** [a]	0.136
S	0.165	**0.846** [a]	0.018	-0.004
Proportion of variance explained	5.00	3.46	1.63	1.20
Cumulative variance	33.3	56.4	67.3	75.3
Eigenvalue	6.90	2.01	1.37	1.02

† CEC, cation exchange capacity; Factor loadings in bold are considered highly weighted

In order to identify soil properties that controlled crop yield the most, mean grain yield was regressed on the scores of the first four PCs. In all sites, CF yields increased significantly ($P<0.001$) with greater total C and N, finer soil texture, greater CEC as well as macro- and micro-nutrient contents with exception of P, Cu, Zn and pH, indicated by correlations with PC1 ($P<0.001$) and PC2 ($P<0.01$) bearing positive loadings with these soil properties. The positive relationship between texture, C, N, nutrients and yield was especially pronounced in the wetter region (AEZ III) for TF (Supplementary Table S1a). In all sites, yields decreased with increasing pH (correlation with PC4, Table 5, with positive loading on pH, Table 4).

Table 1.5. Correlation coefficients between either CF or TF yield (all AEZs together) or CF+TF yield for each AEZ separately and principal components from either soil properties, site variables or management with significance level of P≤0.05.

Farming System	Soil Properties				Site Variables		Management Variables		
	PC1	PC2	PC3	PC4	PC1	PC2	PC1	PC2	PC3
CF All sites	0.05***	0.05**	−0.0002ns	−0.01ns	−0.0002ns	−0.01ns	−0.05**	−0.002ns	−0.004ns
TF All sites	0.004ns	-0.01ns	−0.01ns	−0.01ns	-0.03ns	0.06***	0.05**	0.01ns	0.002ns
CF AEZ I	0.58ns	0.58ns	0.60ns	−0.58ns	0.60ns	−0.58ns	0.01ns	0.0004ns	0.0003ns
CF AEZ II	-0.03ns	0.04ns	-0.03ns	0.001ns	−0.08*	0.03ns	0.4ns	0.01ns	0.01ns
CF AEZ III	0.51ns	0.56ns	0.62ns	-0.53ns	0.73**	0.49ns	−0.01ns	0.05ns	0.05ns

***, **, *, ns: significant at P<0.001, 0.01, 0.05 or not significant, respectively

3.3. Relationship between site variables and yields

Terrain parameters identified and classified five slope positions being valley, lower, flat, middle and ridges while absolute curvature, plan curvature and profile curvature values ranged between -0.205 to 0.131, -0.15 to 0.08 and -0.067 to 0.071. In all sites, univariate analysis show a significant increase in TF grain yields with increase in MAP ($P<0.001$), elevation and slope curvature ($P<0.05$) (Figure 5). Maize yields significantly varied ($P<0.05$) at different slope positions (Figure 6). In drier region (AEZ I), significantly higher yields were observed in valley and flat positions while the ridges had the lowest productivity.

In the wetter region (AEZ III), valley and flat positions showed the lowest yield, and lower slope position had significantly higher yields (Figure 6). Slope position had no effect on yield in the degraded plateau with moderate rainfall (AEZ II).

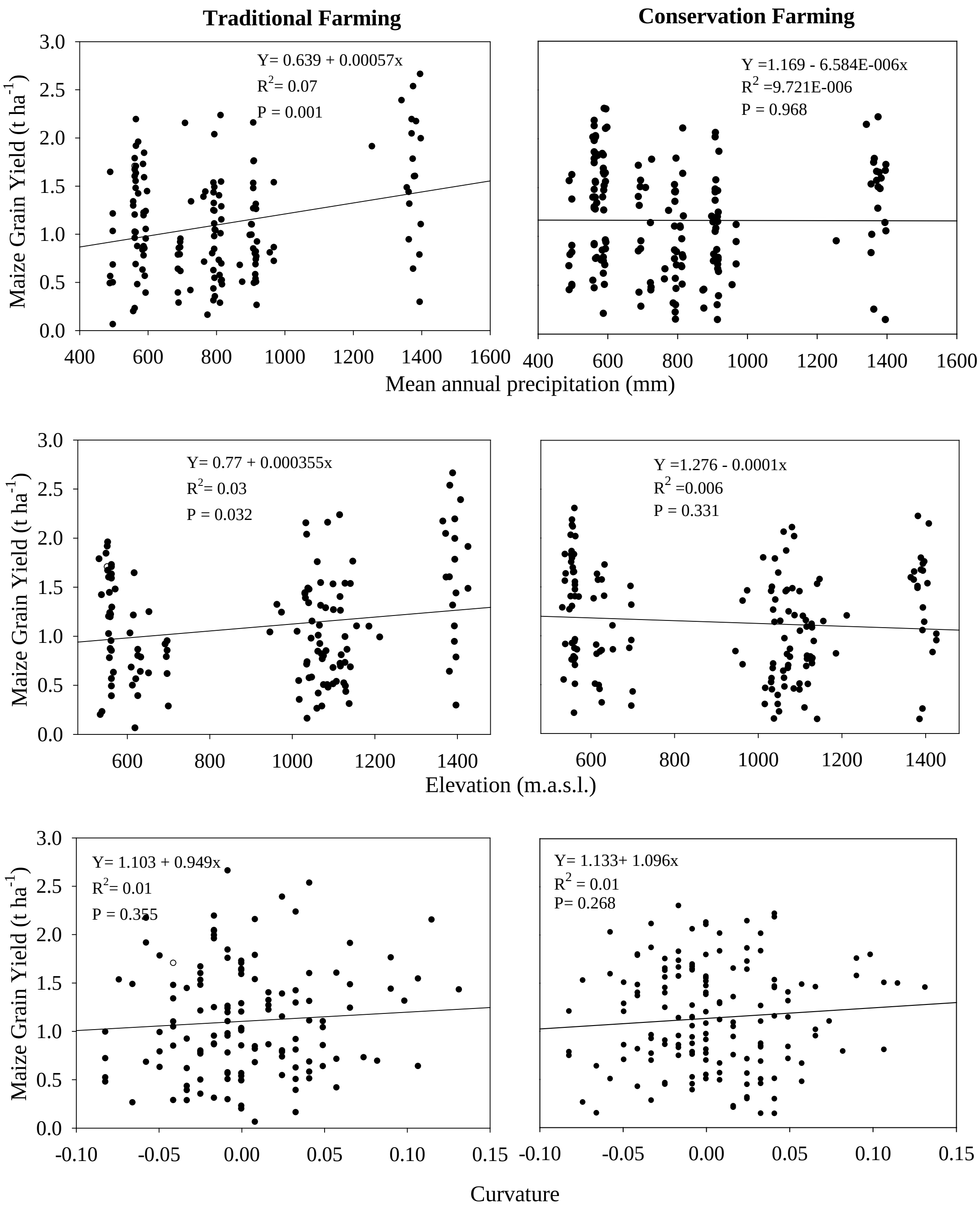

Figure 1.5. Relationship between select site variables and crop yield under conservation and traditional farming in eastern Zambia (n=280).

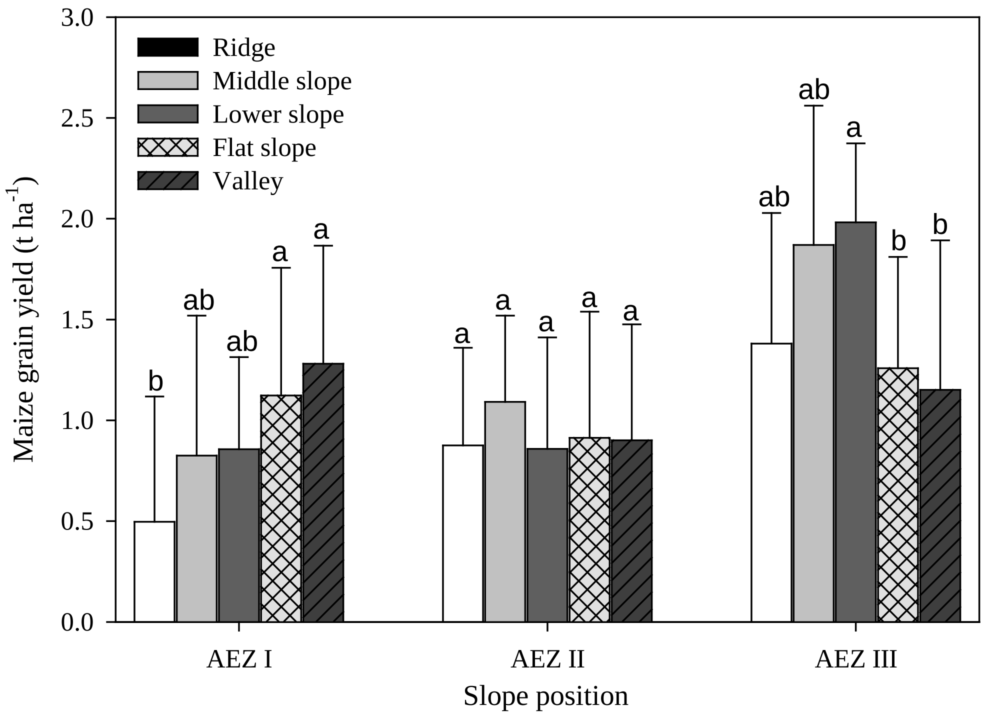

Figure 1.6. Slope position and TF and CF crop yields (error bars represent standard deviations). Comparisons are done for agroecological zone separately (bars with a different letter within a zone are significantly different from each other at $P < 0.05$).

Table 1.6. Site variables investigated with principal component analysis and their summary statistics.

Site variables	PC1	PC2
Rainfall	0.083	**0.885**
Slope aspect	0.008	-0.398
Elevation	0.090	**0.944**
Slope gradient	0.162	**0.727**
Curvature	**0.994** [a]	0.096
Curvature profile	**-0.894**	-0.093
Curvature plan	**0.896**	0.069
Proportion of variance explained	2.63	2.39
Cumulative variance (% of total explained)	37.6	71.7
Eigenvalue	2.86	2.21

[a] factor loadings in bold are considered highly weighted.

In order to group the correlated site variables to the smallest possible subsets representing the majority of variation, PCA was performed using seven site variables. Each of the first two groups or factors had an eigenvalue greater than 1 and were retained for interpretation. The two factors cumulatively explained 71.7% of the total sample variance, but only 5% of total site variation with a maximum of 7% captured by all site properties (Table 6). Relief properties such as absolute, profile and plan curvature dominated PC1 explaining 38% of the total variance while PC2 that explained 34% of the variation had high factor loading for properties such as elevation, rainfall, aspect and slope gradient (Table 6).

To identify the site variables that controlled yields, yield were regressed with PCs. The relationship between slope curvature, topographic relief properties and grain yield varied with location and with the farming system (Table 5, and Supplementary Table S1). Elevation, rainfall and slope gradient (PC2) explaining 34% of the site variability correlated with greater crop yields under TF ($P<0.001$) when all sites were analyzed together. However, in the wetter region (AEZ III) CF yields had strong positive significant correlation ($R = 0.73$; $P<0.01$) in convex slopes but weak negative correlation ($P<0.05$) with yields in moderate rainfall region (AEZ II) (Table 5).

3.4 Management and crop yields

Principal component analysis identified management characteristics that were important for greater yields under CF and TF (Tables 7 and 8). The four components (PC1-4) cumulatively explained 68% of the total sample variance within CF farming (Table 7). Management practices including date of planting (Figure 7) and number of weeding dominated the first factor (PC1 loadings) accounting for 25% of the total variation. PC2 had high loadings from type and amount of soil amendment applied and collectively explained 16% of the sample variance. The highly weighted variables under PC3 were date of soil amendment application and amount of top dressing applied. Similarly, crop rotation from PC4 was selected as a highly weighted variable. The four PCs only captured 4.6% of the CF management variation with 6.9% explainable by management overall (Table 7).

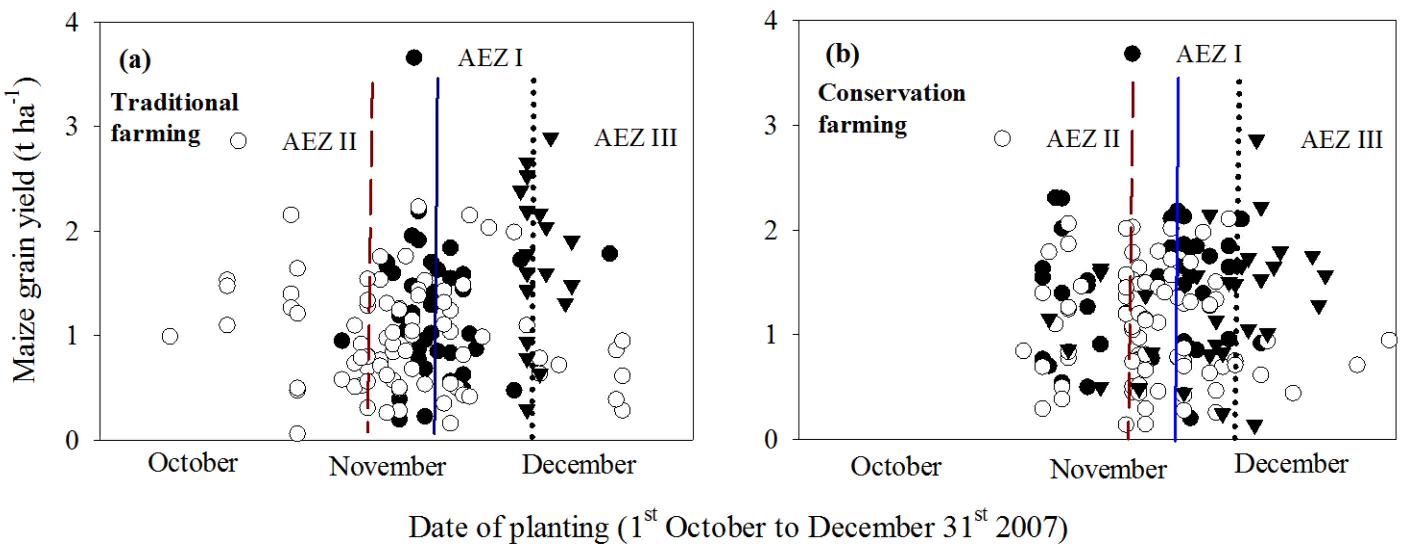

Figure 1.7. Relationship between actual dates of planting and maize grain yield in (a) traditional and (b) conservation farming in each agroecological zone. Dashed line is AEZ II, solid line is AEZ I while dotted line is AEZ III, and represent average dates of planting.

Table 1.7. CF Management characteristics investigated with principal component analysis and their summary statistics.

Management Variables	PC1	PC2	PC3	PC4
Date of planting	**0.857**	0.035	-0.195	0.228
First weeding	**0.858**	0.061	-0.103	-0.009
Second weeding	**0.835**	0.091	0.049	0.108
Third weeding	**0.648**	-0.006	0.351	-0.074
Soil amendment input date	0.260	-0.062	**-0.785**	0.211
Lime applied	-0.004	**0.952**	-0.030	0.036
Basal fertilizer applied	0.115	**0.713**	0.511	0.184
Manure applied	0.132	**0.569**	0.007	-0.473
Compost applied	-0.223	-0.002	0.061	**-0.551**
Top dressing applied	0.168	0.060	**0.776**	0.207
Crop rotation§	-0.033	0.028	0.094	**0.717**
Proportion of variance explained	2.76	1.76	1.67	1.23
Cumulative variance	25.1	41.1	56.3	67.5
Eigenvalue	2.93	2.09	1.35	1.06

[a] factor loadings in bold are considered highly weighted; § represents the crop planted prior to the first year of measurements.

For management under TF, the first three factors of the PCA all had an eigenvalue greater than 1 and cumulatively explained 65.9% of the total sample variance, but only 4.2% of the total management variation with 6.4% of total variation explained by the quantified management variables (Table 8).

Management practices including amount of basal fertilizer, manure and lime applied dominated the first factor (PC1 loadings) accounting for 26 % of the total sample variation under TF. PC2 described by top dressing and weeding date accounted for 23% of total sample variation while PC3 described the amount of compost applied and date of planting (Figure 7).

In order to identify management practices that controlled crop yield the most, mean grain yield was regressed on the scores of the first three PCs. Early planting and weeding (PC1) increased CF yields ($P<0.001$ on PC1, Table 5) but had no effect on TF ($P>0.05$ on PC2; Table 5).

In contrast, the most important factor for TF yield increases were inorganic fertilizer, manure and lime applications (PC1) ($P<0.001$; Table 5). This was especially pronounced in drier regions (AEZ I; Supplementary Table S1a).

Table 1.8. TF Management characteristics investigated with principal component analysis and their summary statistics.

Management Variables	PC1	PC2	PC3
Basal fertilizer applied	**0.757**	0.414	-0.160
Lime applied	**0.929**[a]	-0.099	-0.027
Manure applied	**0.604**	-0.016	0.171
Weeding date	-0.082	**0.819**	-0.035
Top dressing applied	0.173	**0.803**	-0.053
Compost applied	0.005	0.115	**0.902**
Date of planting	-0.061	0.333	**-0.525**
Proportion of variance explained	1.84	1.62	1.15
Cumulative variance	26.3	49.5	65.9
Eigenvalue	2.03	1.52	1.06

[a] factor loadings in bold are considered highly weighted.

Management factors including amount of basal and top dressing applied had significant correlation with TF yield in the drier region while manure was significant in region with moderate rainfall (P<0.05, Table 9). CF yields were correlated significantly with crop rotation (P<0.01) and with third weeding (P<0.05) in the moderate rainfall region.

Table 1.9. Correlation coefficients between TF and CF grain yield and management variables with significant level of $p \leq 0.05$

	TF			CF		
Management variables	AEZ I	AEZ II	AEZ III	AEZ I	AEZ II	AEZ III
Soil amendment input date	n/a	n/a	n/a	0.02ns	0.02ns	0.15ns
Date of planting	0.04ns	0.002ns	−0.004ns	−0.01ns	0.04ns	0.01ns
Basal applied	−0.12*	0.02ns	−0.003ns	−0.04ns	0.02ns	0.01ns
Top dressing applied	−0.12*	−0.04ns	0.0003ns	−0.04ns	0.03ns	0.03ns
Lime applied	n/a	−0.02ns	−0.03ns	−0.03ns	0.02ns	−0.002ns
Manure applied	−0.03ns	−0.06*	−0.04ns	0.05ns	0.02ns	−0.02ns
Compost applied	n/a	n/a	n/a	0.0002ns	0.001ns	n/a
Weeding 1	−0.004ns	−0.0003ns	−0.04ns	0.04ns	0.02ns	0.0001ns
Weeding 2	n/a	n/a	n/a	0.003ns	0.02ns	−0.06ns
Weeding 3	n/a	n/a	n/a	0.01ns	0.06*	−0.07ns
Weeding 4	n/a	n/a	n/a	0.03ns	0.02ns	0.13ns
Crop rotation§	−0.05ns	0.02ns	−0.04ns	0.03ns	0.07**	−0.03ns

***, **, *, ns: significant at P<0.001, 0.01, 0.05 or not significant, respectively. n/a indicates no observation recorded. § represents the crop planted prior to the first year of measurements.

3.5. Comparative relationship of soil, site and management variables to crop yield

Multiple regression analysis using backward elimination was performed to identify the smallest subset of environmental co-variates and management practices for predicting maize grain yield. The regression equation to predict maize grain yield under CF was highly significant and explained about 13% of the yield variation ($P < 0.001$, $R^2 = 0.13$) and retained the properties derived from PCA: Y = 1.164 + 0.097 PC2 Soil + 0.064PC1 management – 0.077PC3 management, suggesting a greater importance of management than soil and site properties across the entire investigated region.

4. Discussions

4.1. Environmental conditions and crop yields

The results of this study show that among the quantified soil properties, finer soil texture, total soil C and total soil N were the most important predictors of yield in the studied region, which confirms earlier reports from tropical regions (Rusinamhodzi et al., 2011). Even though P availability is typically low in the dominant agricultural soils (Lixisols, Acrisols, Ferrasols) in Zambia (Yerokun, 2008), it played a lesser role. Similarly surprising is the lesser importance of pH, despite the fact that pH values ranged from 4.4 to 7.4 and within that range may have significant effects on crop growth. Our findings suggest N as a primary target for soil fertility management across a wide range of soil and climate conditions in Zambia and similar regions in south-east Africa. Using on-station studies at a single location in Zambia, Mafongoya et al. (2006) previously found that lack of N is the primary constraint to maize productivity.

Curvature of the land surface, which describes the shape of the slope, was the most important contributing site factor affecting crop yield. Higher yields observed on lower slopes of the wetter regions (Figure 6) indicate that positive curvature (convex surfaces) improve drainage and hence crop yield (Kravchenko and Bullock, 2000; Fraisse et al., 2001; Li et al., 2001). In comparison, higher yields observed in valley and flat positions in the drier region (AEZ I) reflects the influence of soil surface curvature in concave areas of the slope position (i.e. depressions). A similar trend was reported by several other studies in temperate regions. (Sinai et al., 1981; Timlin et al., 1998; Kravchenko and Bullock, 2000). During periods of drought, areas with concave shape (negative curvature) may provide more plant-available water than areas with convex shape (positive curvature). Relatively low coefficient of determination between yields and site characteristics in AEZ II presumably reflects the fact that slope curvature under moderate climatic conditions is independent of slope position, and is essentially a measure of whether water flow at a point is convergent or divergent.

During periods of drought, slopes with concave shape (negative curvature) may provide more plant-available water than slopes with convex shape (positive curvature) explaining the negative correlation observed between yield and curvature. On the other hand, positive correlations were observed when excessive amounts of water accumulated in the slopes with concave shape in the wetter region (AEZ III) thus reducing yield. The areas with convex shape did not accumulate moisture and thus did not suffer a similar reduction in yield.

Slope position had significant effects on crop yield due to more variable slope gradients. Lower yields experienced in ridges of the drier region (Figure 6) could have resulted from inherently less productive ridges due to limitations in water storage capacity and other soil physical and chemical constraints (Wright et al., 1990). Observed results were consistent with those reported in the literature. Changere and Lal (1997), and McConkey et al. (1997) all observed higher yields at lower slopes positions and lower yields at higher slope positions.

Elevation correlated negatively with crop yields in the drier regions and positively in the wetter regions (Table 5). In most cases, the influence of elevation and slope gradient on yield is reflected in water availability and this effect is more readily observed under extreme weather (either wet or dry) conditions and field topography (Kravchenko and Bullock, 2000).

4.2. Relative importance of soil, site and management for crop yields

Management was more important than soil or site conditions in determining crop yield. Typically, higher yields are shown to result from the benefits of timely planting at the onset of rainfall. Maize yields fall by 1-2% for every day delay in planting after the first rains (Haggblade, 2003). Also weeding has been described as one of the most important factors determining maize growth in Africa. Silwana and Lucas (2002) obtained highest maize grain yields in weeded plots than unweeded plots in South Africa.

Important differences were observed to which management and environmental conditions either CF or TF responded with greater crop yield. In this study, finer soil texture, greater amounts of total soil C and N, CEC and available nutrients were the most important environmental conditions for success in crop yields by CF, whereas site properties such as rainfall, elevation and slope were more important for yields under TF. This suggests that yield gains from CF basins were strongly associated with improved water availability in low-rainfall areas rather than from the poor organic additions with insufficient supply of nutrients.

Similarly, yields under CF and TF responded differently to management interventions. Greater yields under CF depended mostly on early planting and weeding, whereas TF yields benefited the most from fertilizer, lime and manure applications. The greater dependency of crop yields on manual weeding under CF may be explained by the lack of weed control through tillage. Lack of tillage results in increased weed pressure (Kayode and Ademiluyi, 2004). Weed control is essential for optimum crop growth under reduced tillage. For example, Tittonell et al. (2007a) observed a wider range of yield gains under little weed pressure, suggesting that greater yields can only be achieved if weeds are appropriately managed.

The well-known benefits of early planting described earlier is one of the strengths of CF, which allows planting well before that would be possible with TF (Haggblade & Tembo, 2003, Tittonell et al., 2007a). The opportunity to plant early in TF systems is limited and the range of possibilities is greatly reduced, since the soil can only be tilled after the first rainfall events. Therefore, early planting was not a major factor for the farmers practicing TF (Figure 7).

4.3. Conservation farming impacts

This study shows that maize yields did not increase when practicing CF in comparison to TF. Various mechanisms that may help increase crop yield in CF when applied under controlled conditions on a research station or on-farms demonstration plots may not be effective when practiced by farmers (Tittonell et al., 2008). Adopting CF requires substantial changes in farming practice that include minimum tillage, early land preparation of permanent planting stations and planting, permanent soil cover (retention of crop residue instead of burning) and crop rotation (CFU, 2003).

One major constraint for achieving optimum yields with CF is the access to suitable soil amendments. Baudron et al (2012) reported negative cotton yields when farmers supplied their own input in Zimbabwe. The different rates and sources of amendments applied varied significantly among farmers. Limited amounts and the low quality of compost applied by farmers in the studied dry regions (AEZ I) decreased the utility of organic amendments as a source of nutrients, whereas farmers in the wetter regions have access to manure from livestock with greater nutrient contents. Even in locations where animal manure is available, farmers often leave the cattle dung exposed in pens for extended periods of time, which can significantly decrease its nutrient value (Markewich et al., 2010) and households owning cattle did not even use cattle manure as an amendment for maize production. Twomlow et al. (2008b) made similar observations in Zimbabwe.

The benefit of the basins with respect to an improvement in soil chemical and physical attributes was likely not achieved, even though such benefits are typically stated as an important advantage of CF (Bationo, 2008). One reason probably lies in the inability of farmers to maintain identical permanent basin positions. Exact measurement of CF basin grids theoretically enables placement in close proximity to the seeds and a cumulative effect of organic amendments over time. However, farmers dig basins later in the season when it is dry (ZCATF, 2009) and evidence of exact basin location is often lost. Hence, the concept of permanent planting stations that allow a more precise input and a better concentration of nutrients to encourage soil fertility accrual is often not achieved.

In contrast to the nutrient and C benefits, planting basins did likely improve water availability as seen from the crop responses in the dry region. Yield improvement significantly increased with lower rainfall. The positive effect of CF compared to TF was higher for drier areas with poor rainfall compared to areas with adequate rainfall (Figure 5). The benefit of CF may therefore be mainly a function of harvesting water and concentrating rainfall in the root zone through the basins. Other studies have also demonstrated improved water availability in CF (Derpsch et al., 1986; Thierfelder and Wall, 2009).

The frequency of weeding was critical to achieve high yields specifically in CF. Shumba et al. (1989) and Vogel (1993) calculated that delaying first weeding in maize by more than 30 days after crop emergence led to a decrease in maize grain yield of 28% in sub-humid Zimbabwe. Although farmers are familiar with the advantages of keeping the fields free of weeds by weeding two to three times per season, manual weeding is labor intensive (Giller et al., 2009). Observed weeding was conducted manually with a hand-hoe in between rows and around the basins. However, Mashingaizde (2009) reported that although planting basins had a less diverse weed community, basins had significantly higher weed density as compared to conventional farming during the critical growth period in maize. Hence, maize yield decline is likely to occur in planting basins. Moreover, farmers stop weeding once the maize reaches maturity thereby increasing the weed seed bank. This implies that early weeding must be conducted to avert yield loss.

An additional obstacle in achieving greater yields with CF is likely an insufficient soil cover. Permanent soil cover with crop residues offer benefits such as increased soil organic C (Mann et al., 2002) with all its ancillary benefits for soil fertility (Hobbs, 2007), weed suppression (Mulvaney et al., 2011), and consequent greater and more stable yields and water infiltration (Govaerts et al., 2007). However, the high turnover of crop residues, accidental or deliberate communal grazing (Rockström et al., 2009; Erenstein et al, 2012), customary burning or attack by termites limits availability of organic resources (Giller et al., 2009). Minimum tillage with little or no soil cover may lead to lower yields than even TF with full tillage (e.g. Akinyemi et al., 2003; Alabi and Akintunde,2004).

4.4. Recommendations for improving CF

The results indicate important management constraints of realizing benefits of CF, rather than merely biophysical constraints or constraints of fertilizer inputs. This is encouraging as it suggests that appropriate management will allow significant improvements in productivity, and that the low yields are not primarily constrained by soil and climate conditions that cannot be easily altered. However, even optimization of those management interventions that do not rely on external inputs can pose significant hurdles, such as early planting and weeding. Therefore, intensive manual weeding would be recommended in basins and slashing around the basins. Future research is needed to measure and compare weed densities in basins and rows.

Conservation farming will likely be effective in conserving soil and increasing production only if most of the practices are applied together. Reduced tillage and installation of basins will address issues like erosion and water harvesting but equal attention must be paid to appropriate planting schedules and weed management practices. Use of basins in the lower rainfall area for water harvesting would be appropriate while basins on ridges or hills would be recommended for the high rainfall area to improve drainage. Therefore, CF must be applied as a system of integrated techniques and not a set of individual practices.

The participatory action research partly adopted in these trials, where farmers were involved in identifying problems and solutions, as well as assessing the results and adapting to the system, proved to be an important asset in order to raise farmers' interest and commitment to address management constraints. The challenges discussed with farmers involved compost and mulch preparation that requires farmers to physically prepare and move voluminous quantities of organic material and that often affects labor input (Vissoh et al., 1998). Farmers indicated that mulch is destroyed by animals and termites, and discontinued the use since they could not find immediate benefits. Mashingaidze et al. (2004) noted that visible benefits associated with mulching may take longer to be realized. Further, the communal land tenure system only allows limited control of grazing the livestock on crop residues *in situ* and burning of crop residues. The result of the tenure system is virtually no residue cover, and basins that are rarely dug in the same place as during the last cropping season. Maintenance of the same planting basins should reduce the labor required in subsequent seasons. However, fixed planting stations pose challenges in rotations due to differences in spacing requirements for cereals and legumes. Hence, the concept of permanent planting stations with precise input application for concentration of nutrients to encourage soil fertility build-up is not achieved. However it must be noted that most farmers tend to start digging planting basins in the months of September to October (even up to November), as a result they consider digging of planting basins a laborious exercise yet they squeeze in the basin digging into a short space of time before the onset of the rains (ZCATF, 2009). Farmers are aware of the need to apply manure to increase fertility within the basin. Access to manure remains an issue to those farmers without livestock. Despite the knowledge of manure application, farmers have little knowledge and limited experience in preparation of manure for cropping purposes. The general trend is for the cattle dung to be left exposed throughout the year in pens, and applied when not fully decomposed. The appropriate time of application is another important issue that farmers tend to disregard. Farmers apply manure during planting which increases the labor involved. Since most of the farmers are rushing to finish the application of manure and planting (done on the same date), they tend to disregard the fact that the seed-manure contact may affect germination rates.

5. Conclusions

The results indicate that CF does not provide advantages over conventional farming practice unless permanent planting basins and high-quality organic inputs can be implemented. Due to the observed inability to maintain basins at the same location, an accrual of soil fertility benefits is hampered even over prolonged periods of time. The main advantage of CF remains improved water harvesting under dry conditions. Further research is required to confirm which yield improvement would be important for farmers in the sub-humid areas, as their concern primarily is how to address the risk of yield reductions during water scarcity.

Since crop management such as early planting and weeding was more important for CF while nutrient input dominated the success of TF, subsidizing external inputs such as fertilizers will be less successful for CF than TF. The varied biophysical conditions and socio-economic circumstances of smallholder farmers illustrates the importance of a flexible approach with room for adaptations to local conditions, and assessment where CF practices may work best and which farmers in any given community may benefit the most.

REFERENCES

Aagaard, P., Gibson, G. 2003a. Conservation farming in Zambia. Conservation farming handbook for hoe farmers in Agro Ecological 1 & II Flat Culture. Lusaka Conservation Farming Unit.

Aagaard, P., Gibson, G. 2003b. Conservation farming in Zambia. Conservation farming handbook for hoe farmers in Agro Ecological Region III, the basics. Lusaka, Conservation Farming Unit.

Akinyemi, J.O., Akinpelu, O.E., Olaleye, A.O. 2003. Performance of cowpea under three tillage systems on an Oxic Paleustalf in southwestern Nigeria. Soil Tillage and Research 72, 75–83.

Alabi, S., Akintunde, O. 2004. Effect of tillage method on soil properties and performance of groundnut (Arachis hypogaea L.) in Southwestern Nigeria. Journal of
Sustainable Agriculture and Environment 6, 22–29.

Bationo, A. 2008. Integrated Soil Fertility Management Options for Agricultural Intensification in the Sudano-Sahelian Zone of West Africa. Academy of Science Publishers, Nairobi.

Bationo, A., Ayuk, E., Ballo, D., Kon'e, M. 1997. Agronomic and economic evaluation of Tilemsi phosphate rock in different agroecological zones of Mali. Nutrient Cycling in Agroecosystems 48, 179–189.

Baudron, F., Anderson, J.A., Corbeels, M., Giller, K.E. 2012. Failing to yield? ploughs, conservation agriculture and the problem of agricultural intensification, an example from the Zambezi valley, Zimbabwe. The Journal of development studies 48, 393-412.

Blanco-Canqui, H., Lal, R., Post, W.M., Owens, L.B. 2006. Changes in long-term no-till corn growth and yield under different rates of stover mulch. Agronomy Journal 98, 1128-1136.

Boughton, D., E. Crawford, M. Krause, and B. de Frahan. 1990. Economic Analysis of On-farm Trials: A Review of Approaches and Implications for Research Program Design. MSU Department of Agricultural Economics Staff Paper No. 90-78. East Lansing: Michigan State University.

Bouma, J. 1999. Land evaluation for landscape units. In M.E. Sumner (Ed), Handbook of soil science. CRC Press, Boca Raton, FL, pp. E393-E412.

Bowerman, B.L., O'Connell, R.T. 1990. Linear statistical models, An applied approach. 2nd ed. Duxbury Press, Belmont, CA.

Brejda, J.I., Moorman, T.B., Karlen, D.L., Dao, T.H. 2000. Identification of regional soil quality factors and indicators. I. Central and Southern high plains. Soil Science Society of America Journal 64, 2115–2124.

Changere, A., Lal, R. 1997. Slope position and erosional effect position soil properties and corn production on a Miamian soil in central Ohio. Journal of Sustainable Agriculture 11, 5–21.

Chidumayo, E.N., Frost. P. 1996. Population biology of miombo trees. In Campbell, B. (Ed) The miombo in transition, woodlands and welfare in Africa. Centre for International Forestry Research.

Chiwele, D., McKenzie, J. 1996. Zambia, Agricultural Sector Performance Analysis. University of Zambia, Institute for African Studies.

Ciha, A.J. 1984. Slope position and grain yield of soft white winter wheat. Agronomy Journal 76, 193–196.

Cox, M.S., Gerard, P.D., Abshire, M.J. 2006. Selected soil properties' variability and their relationships with yield in three Mississippi fields. Soil Science 171, 541–551.

DeGloria, S.D. 1993. Visualizing soil behavior. Geoderma 60, 41-55.

Derpsch, R., Sidiras, N., Roth, C.F. 1986. Results of studies made from 1977 to 1984 to control erosion by cover crops and no-tillage techniques in Parana´ , Brazil. Soil and Tillage Research 8, 253–263.

Erenstein, O. 2002. Crop residue mulching in tropical and semi-tropical countries: an evaluation of residue availability and other technological implications. Soil Tillage and Research 67, 115–133.

Erenstein, O. 2003. Smallholder conservation farming in the tropics and sub-tropics: a guide to the development and dissemination of mulching with crop residues and cover crops. Agriculture Ecosystems and Environment 100, 17–37.

Erenstein, O., Sayre, K., Wall, P., Hellin, J., Dixon, J. 2012. Conservation agriculture in maize and wheat based systems in the sub tropics, lessons from adaptation and initiatives in south Asia, Mexico and southern Africa. Journal of Sustainable Agriculture 36, 180-206.

Fahnestock, P., R. Lal, Hall, G.F. 1996. Land use and erosion effects on two Ohio soils, II. Crop yields. Journal of Sustainable Agriculture 7, 85–100.

FAO website on Conservation Agriculture: http://www.fao.org/ag/ca

FAOstat. 2010. Food and Agriculture Organization of the United Nations statistical database, http://faostat.fao.org/site/567 (accessed in June 2012).

Fatondji, D., Martius, C., Bielders, C., Vlek, P., Bationo, A., Gerard, B. 2006. Effect of planting technique and amendment type on pearl millet yield, nutrient uptake, and water use on degraded land in Niger. Nutrient Cycling in Agroecosystems 76, 203–217.

Fraisse, C.W., Sudduth, K.A., Kitchen, N.R. 2001. Delineation of site-specific management zones by unsupervised classification of topographic attributes and soil electrical conductivity. Transactions of America Society of Engineers 44:155–166.

GEF, 2003. What Kind of World? The Challenge of Land Degradation, Global Environment Facility (GEF) (2003) p. 4.

Giller, K.E., Witter, E., Corbeels, M., Tittonell, P. 2009. Conservation agriculture and smallholder farming in Africa, The heretics' view. Field Crops Research 114, 23-34.

Goovaerts, P. 1998. Geostatistical tools for characterizing the spatial variability of microbiological and physico-chemical soil properties, Biology and Fertility of Soils 27, 315–334.

Haggblade, S., Tembo, G. 2003. Conservation farming in Zambia. EPTD Discussion Paper. Environment and Production Technology Division, International Food Policy Research Institute.

Hobbs, P.R. 2007. Conservation agriculture: what is it and why is it important for future sustainable food production? Journal of Agricultural Science 145, 127- 137.

Matthews, R. B., Holden, S.T., Volk, J., Lungu, S. 1992. The potential of alley cropping in improvement of cultivation systems in the high rainfall areas of Zambia I. Chitemene and Fundikila. Agroforestry systems 17, 219-240.

Jagadamma, S., Lal, R., Hoeft, R.G., Nafziger, E.D., Adee, E.A. 2007. Nitrogen fertilization and cropping system effects on soil organic carbon and total N pools under chisel-plow tillage in Illinois. Soil and Tillage Research 95, 348–356.

Jenness, J. 2010. Topographic Position Index (tpi_jen.avx) extension for ArcView 3.x, v. 1.2. Jenness Enterprises. Available at: http://www.jennessent.com/arcview/tpi.htm.

Jiang, P., Thelen, K.D. 2004. Effect of soil and topographic properties on crop yields in a north-central corn-soybean cropping system. Agronomy Journal 96, 252–258.

Johansen, C., Haque, M.E., Bell, R.W., Thierfelder, C., Esdaile, R.J. 2012. Conservation agriculture for small holder rainfed farming: opportunities and constraints of new mechanized seeding systems. Field Crops Research 132, 18–32.

Kaiser, H.F. 1960. The application of electronic computers to factor analysis. Educational and psychological measurement 20, 141–151.

Kaspar, T. C., Pulido, D. J., Fenton, T. E., Colvin, T. S., Karlen, D. L., Jaynes, D. B., Meek, D.W. 2004. Relationships of corn and soybean yield to soil and terrain properties. Agronomy Journal 96, 700–709.

Kayode, J., Ademiluyi, B. 2004. Effect of tillage methods on weed control and maize performance in southwestern Nigeria. Journal of Sustainable Agriculture 23, 39–45.

Kravchenko, A.N., Bullock, D.G. 2000. Correlation of grain yield with topography and soil properties. Agronomy Journal 92, 75–83.

Lal , R., Reicosky, D.C., Hanson, J.D. 2007. Evolution of the plow over 10,000 years and the rationale for no-till farming. Soil and Tillage Research 93, 1-12.

Lal, R. 1987. Managing the soils of sub-Saharan Africa. Science 236, 1069-1075.

Li, H., Lascano, R.J., Booker, J., Wilson, L.T., Bronson, K.F. 2001. Cotton lint yield variability in a heterogeneous soil at a landscape scale. Soil and Tillage Research 58, 245–258.

Mafongoya. P., Bationo, A., Kihara, J., Waswa, B. 2006. Appropriate technologies to replenish soil fertility in southern Africa. Nutrient Cycling in Agroecosystems 76,137–151.

Mallarino, A.P., Oyarzabal, E.Z., Hinz, P.N. 1999a. Interpreting within-field relationships between crop yields and soil and plant variables using factor analysis. Precision Agriculture 1, 15–25.

Mallarino, A.P., Pecinovsky, K. 1999b. Effect of crop rotation and nitrogen fertilization on crop production over a 20-year period. In Annual Progress Reports-1998. Northeast Research and Demonstration Farm. ISRF98-13. Iowa State University, Ames, pp. 13–16.

Mallarino, A.P., Rueber, D. 1999. Crop rotation and nitrogen fertilization for crop production. In Annual Progress Reports-1998. Northern Research and Demonstration Farm. ISRF98-22. Iowa State University, Ames, IA, pp. 30–33.

Mann, L., Tolbert, V., Cushman, J. 2002. Potential environmental effects of corn (Zea mays L.) stover removal with emphasis on soil organic matter and erosion. Agriculture, Ecosystem and Environment 89, 149-166.

Mansfield, J.E., Bennett, J.G., King, R.B., Lang, D.M., Lowton, R.M. 1975. Current land-use, land resources of the Northern and Luapula provinces, Zambia. A Reconnaissance Assessment: Land Resource Study No. 19, Vols. 1–6. Ministry of Overseas Development, Surbiton, Surrey, UK.

Markewich, H.A., Pell, A.N., Mbugua, D.M., Cherney, D.J.R., van Es, H.M., Lehmann, J., Robertson, J.B. 2010. Effects of storage methods on chemical composition of manure and manure decomposition in soil in small-scale Kenyan systems. Agriculture, Ecosystems and Environment 139, 134-141.

Martens, H., Naes, T., 1989. Multivariate Calibration. Wiley, New York, USA, pp. 97–108.

Matthews, R.B., Holden, S.T., Volk, J., Lungu, S. 1992. The potential of alley cropping in improvement of cultivation systems in the high rainfall areas of Zambia. Agroforestry Sytems 17, 219-261.

Mazvimavi, K., Twomlow, S. 2009. Socioeconomic and institutional factors influencing adoption of conservation farming by vulnerable households in Zimbabwe. Agricultural Systems 101, 20-29.

McConkey, B.G., Ulrich, D.J., Dyck, F.B. 1997. Slope position and subsoiling effects on soil water and spring wheat yield. Canadian Journal of Soil Science 77, 83–90.

Miller, M.P., Singer, M.J., Nielsen, D.R. 1988. Spatial variability of wheat yield and soil properties on complex hills. Soil Science Society of America Journal 52, 1133–1141.

Oldrieve, B. 1993. Conservation farming for communal, small-scale, resettlement and cooperative farmers of Zimbabwe: A Farm Management Handbook. Harare Rio Tinto Foundation.

Osmond, D.L., Riha, S.J. 1996. Nitrogen fertilizer requirements for maize produced in the tropics, a comparison of three computer based recommendation systems. Agricultural Systems 50, 37–50.

Ovalles, F.A., Collins, M.E. 1986. Soil–landscape relationships and soil variability in north central Florida. Soil Science Society of America Journal 50, 401–408.

Qiu, Y., Fu, B.J., Wang, J., Chen, L.D. 2001. Soil moisture variation in relation to topography and land use in a hillslope catchment of the Loess Plateau, China. Journal of Hydrology 240, 243–263.

Richardson, J.L., Bigler, R.J. 1984. Principal component analysis of prairie pothole soils in North Dakota. Soil Science Society of America Journal 48, 1350–1355.

Rockström, J., Falkenmark, M. 2000. Semiarid crop production from a hydrological perspective, gap between potential and actual yields. Critical Reviews in Plant Sciences. 19, 319–346.

Rockström, J., Kaumbutho, P., Mwalley, J., Nzabi, A.W., Temesgen, M., Mawenya L., Barron, J., Mutua, J., Damgaard-Larsen, S. 2009. Conservation farming strategies in east and southern Africa, yields and rain water productivity from on-farm action research. Soil and Tillage Research 103, 23-32.

Rusinamhodzi, L., Corbeels, M. van Wijk, M.T, Rufino, M.C., Nyamagara, J., Giller, K.E. 2011. A meta-analysis of long-term effects of conservation agriculture on maize grain yield under rain-fed conditions. Agronomy for sustainable development 31, 657- 673.

Sanchez, P.A. 2002 Soil fertility and hunger in Africa. Science 295, 2019–2020.

Sayre, K., Hobbs, P. 2004. The raised-bed system of cultivation for irrigated production conditions. In Sustainable agriculture and the Rice-Wheat system. Lal R.

P. Hobbs, N. Uphoff, and D.O. Hansen (Eds). Ohio State Univ., Columbia, Ohio, USA. pp. 337-355.

Sena, M.M., Frighetto, R.T.S., Valarini, P.J., Tokeshi, H., Poppi, R.J. 2002. Discrimination of management effects on soil parameters by using principal component analysis: a multivariate analysis case study. Soil and Tillage Research 67, 171–181.

Shumba, E.M., Waddington, S.R., Rukuni, M. 1992. Use of tine-tillage, with atrazine weed control, to permit earlier planting of maize by smallholder farmers in Zimbabwe. Experimental Agriculture 28, 443–452.

Silwana, S.T., Lucas, E. 2002. The effect of planting combinations and weeding on the growth and yield of component crops of maize/bean and maize/pumpkin intercrops. The Journal of Agricultural Science 138, 193-200.

Sinai, G., Zaslavsky, D., Golany, P. 1981. The effect of soil surface curvature on moisture and yield-beer sheba observation. Soil Science 132, 367-375.

Sivakumar, M.V.K., Wallace, J.S. 1991. Soil water balance in the Sudano-Sahelian zone: need, relevance and objectives of the workshop. In Soil Water Balance in the Sudano-Sahelian Zone. Proceedings Niamey Workshop, February 1991.

Smaling, E.M.A., Nandwa, S.M., Janssen, B.H. 1997. Soil fertility is at stake! In Replenishing Soil Fertility in Africa, An Investment in Natural Resource Capital, SSSA Special Publication Number 51, pp. 47–61. SSSA, Madison, MI.

Stoorvogel, J.J., Smaling, E.M.A. 1998. Research on soil fertility decline in tropical environments, integration of spatial scales. Nutrient Cycling in Agroecosystems 50, 151–158.

Stromgaard, P. 1984. The immediate effect of burning and ash fertilization. Plant and Soil 80, 321-335.

Stromgaard, P. 1990. Effects of mound cultivation on concentration of nutrients in a Zambian miombo woodland soil. Agriculture Ecosystems and Environment 32, 295-313.

Swan, A.R.H., Sandilands, M. 1995. Introduction to Geological Data Analysis. Blackwell, London, pp. 1–446.

Tan, Z.X., Lal, R., Smeck, N.E., Calhoun, F.G. 2004. Relationships between surface soil organic carbon pool and site variables. Geoderma 121, 187–195.

Timlin, D.J., Pachepsky, Y., Snyder, V.A., Bryant, R.B. 1998. Spatial and temporal variability of corn grain yield on a hillslope. Soil Science Society of American Journal 62, 764–773.

Tittonell, P., Vanlauwe, B., de Ridder, N., Giller, K.E. 2007. Heterogeneity of crop productivity and resource use efficiency within smallholder Kenyan farms: soil fertility gradients or management intensity gradients? Agricultural Systems 94,376–390.

Tittonell, P., Vanlauwe, B., Corbeels, M., Giller, K.E. 2008. Yield gaps, nutrient use efficiencies and response to fertilisers by maize across heterogeneous smallholder farms of western Kenya. Plant and Soil 313, 19–37.

Thierfelder, C., Wall, P.C. 2009. Effects of conservation agriculture techniques on infiltration and soil water content in Zambia and Zimbabwe. Soil and Tillage Research.

Twomlow, S., Urolov, J.C., Jenrich, M., Oldrieve B. 2008. Lessons from the field Zimbabwe's Conservation Agriculture Task Force. Journal of SAT Agricultural Research 6 (11 pages).

Twomlow, S., Rohrbach, D., Dimes, J., Rusike, J., Mupangwa, W., Ncube, B., Hove, L., Moyo, M., Mashingaidze, N., Mahposa, P. 2008. Micro-dosing as a pathway to
Africa's Green Revolution, evidence from broad-scale on-farm trials. Nutrient Cycling in Agroecosystems 88, 3–15.

UNEP/ISRIC, 1991. World Map of the Status of Human-Induced Soil Degradation (GLASOD). An Explanatory Note (2nd ed.). UNEP, Nairobi, Kenya, and ISRIC, Wageningen, Netherlands.

Verhulst, N., Govaerts, B., Verachtert, E., Castellanos-Navarrete, A., Mezzalama, M., Wall, P.,Deckers, J., Sayre, K.D. 2010. Conservation Agriculture, Improving Soil Quality for Sustainable Production Systems? In Lal, R., Stewart, B.A. (Eds.), Advances in Soil Science: Food Security and Soil Quality. CRC Press, Boca Raton, FL, USA, pp. 137-208.

Vissoh, P.V., Manyong, V.M., Carsky, R.J., Osei-Bonsu, P., Galiba, M. 1998. Green
manure cover crop systems in West Africa: experiences with mucuna. In Buckles, D., Eteka, A., Osiname, O., Galiba, M., Galiano, G. Eds. Cover crops in West Africa
contributing to sustainable agriculture. IDRC, Ottawa, Canada.

Vogel, H. 1993. Tillage effects on maize yield, rooting depth and soil–water content on sandy soils in Zimbabwe. Field Crops Research 33, 367–384.

Wall, P.C. 2007. Tailoring Conservation Agriculture to the needs of small farmers in developing countries, an analysis of issues. Journal of Crop Improvement 19, 137-155.

Wander, M.M., Bollero, G.A. 1999. Soil quality assessment of tillage impacts in Illinois. Soil Science Society America Journal 63, 961–971.

Yerokun, O. A. 2008. Chemical characteristics of Phosphorus in some representative benchmark soils of Zambia. Geoderma 147, 63-68.

Zimbabwe Conservation Agriculture Task Force (ZACTF). 2009. Farming for the future. A Guide to Conservation Agriculture in Zimbabwe. Zimbabwe, Zimbabwe Conservation Agriculture Task Force, 57 pp.

CHAPTER 2

MAIZE YIELD UNDER CONSERVATION FARMING WITH DIFFERENT ORGANIC AND INORGANIC AMENDMENTS ALONG A WIDE ENVIRONMENTAL GRADIENT

Abstract

On a wide environmental gradient across three major agroecological zones of Zambia, we investigated the effects of nutrient additions using different organic and inorganic amendments on nutrient uptake and crop yields under conservation farming (CF). The ability of additions of stable organic matter (biochar) to enhance productivity by nutrient delivery was compared with the ability of labile organic matter (gliricidia and animal manure) to increase productivity largely by improved nutrient availability. Average maize grain yield in all sites ranged between 1.1 to 4 t ha^{-1}. Higher crop yields were observed in wetter region (3.4 ±7.9 t ha^{-1}) followed by drier region (2.6±6.7 t ha^{-1}) while on degraded plateaus, yields were the lowest (2.1 ±6.8 t ha^{-1}). Absolute increase in grain productivity by organic amendments additions was on average 14% higher in wetter (P<0.05) than the drier region. Application of inorganic resources (N-P-K at 200-100-100 kg ha^{-1}) with biochar and manure had the highest effect in the degraded plateau with relative yield increase compared to applications of local compost without fertilizer of 320% and 300% respectively, whereas lowest relative yield increase with organic additions was observed with 0.4-t C ha^{-1} manure (46%) and gliricidia (24%) in the same region. Biochar additions had achieved greater (P=0.008) relative yield increase in

the degraded plateau in contrast to drier region while additions of gliricidia produced (*P*=0.03) higher relative yield increase in the drier than wetter region. Greater mean annual rainfall only led to an increase in crop yields if a combination of organic amendments and inorganic fertilizer was applied, but not without inorganic fertilization (*P*<0.05). In addition, manure additions at 0.4 t C ha^{-1} without inorganic fertilizer did not improve crop P nutrition in both the wettest and driest studied region. Inorganic additions increased N concentrations only in the driest region while fully fertilized manure also enhanced N and P concentrations in the wetter region. Foliar K and Mg concentrations increased with biochar additions in comparison to manure where both received fertilizer in both degraded plateau and wettest studied regions. The principal component analysis (PCA) performed with 21 soil properties, site variables and environmental co-variates demonstrates that pre-existing soil fertility (soil organic C and nutrient availability) is the most important factor at all sites for improved yields and nutrient uptake with organic additions (*P*<0.05). Finer soil texture led to greater yields with compost additions without inorganic fertilizer (*P*=0.001) and when manure was applied with or without inorganic fertilizer (*P*=0.02) but not with biochar additions. Additions of biochar with inorganic fertilizer in wetter region enhanced maize Ca uptake (*P*=0.03) at lower pH (*P*=0.005) and higher rainfall (*P*=0.05).

1.Introduction

Increasing productivity in smallholder agriculture in Africa is critical to achieve the millennium development goals (Andriesse et al., 2007). Land productivity in sub-Sahara Africa (SSA) can potentially be increased by optimizing locally available resources through nutrient management and water conservation or develop marginal lands for production. Conversion of natural ecosystems to agricultural production remains a common practice in southern Africa (Lewis et al., 2011) to increase crop production instead of increasing production per unit area. The consequence of this anthropogenic impact on land use alteration is land degradation as a result of continuous cultivation and leads to loss of soil carbon and total nitrogen (Solomon et al., 2007). Tillage disrupts soil physical, biological and chemical mechanisms of soil organic matter (SOM) stabilization, a key element in soil C dynamics by exposing it to microbial degradation and erosion.

Maintenance and improvement of SOM is fundamental to soil productivity and determines sustainable management of agricultural lands (Bationo et al., 2007; Bationo and Vlek, 1997). However, management of spatial and temporal variability of soil fertility in southern Africa poses a major challenge for increasing crop productivity in smallholder systems. Currently, productivity is critically limited by soil N and P availability (Tittonell et al., 2008) and is dependent on external nutrient inputs (Chivenge et al., 2011). This is caused primarily by negative soil nutrient balances as a result of farming practices with low or no additions of nutrients (Smaling et al., 1997; Sanchez 2002; Cobo et al., 2010). Available organic amendments are often of poor quality (Mugwira and Murwira, 1997) and insufficient to maintain soil fertility (Palm et al., 2001) and utilization of fertilizers is limited by physical access (Larson & Frisvold, 1996) and cost (Sanchez, 2002).

The combination of organic and inorganic resources is progressively gaining recognition (Palm et al., 1997, Smaling et al.,1997) as one of the appropriate ways of addressing soil fertility depletion in low-external input systems (Palm et al., 1998; Mugendi et al.,1999), especially in southern Africa (Mafongoya, et al., 2006; Mtambanengwe et al., 2006). Long-term combinations of both organic and inorganic nutrient sources may lead to enhanced nutrient availability (Palm et al., 1997), synchronization of nutrient release and uptake by crops (Bekunda et al., 1997; Mugendi et al., 1999) and positive effects on soil properties (Wallace, 1996). However, the effects of applied materials vary with their limited availability (Zingore et al., 2008), timing of their relative application, organic material type and management (Palm et al., 1997; Mtambanengwe et al., 2006; Zingore et al., 2008) and soil types and environmental factors (Kang, 1993; Schroth et al., 1995), about which little is known.

The constraints to nutrient availability may vary widely between soil types and may reach from predominantly N limitation in dry areas to predominantly P limitation in wet regions (Vitousek & Sanford, 1986; Vitousek et al., 2010). In the humid tropics soil mineralogy is generally dominated by low-activity or variable-charge clays which strongly adsorb P leading to low P availability (Sollins et al., 1988) and fertilizer use efficiency (Baligar & Bennett, 1986). Organic matter additions may improve availability of soil P or added fertilizer P by decreasing P adsorption to low-activity clays (Lehmann et al., 2001; Nziguheba et al., 2002). In addition, different organic matter amendments may alter the pH and thereby decrease or increase P availability as seen for biochar (Lehmann et al., 2003). The result of combinations of organic matter amendments and inorganic fertilizer additions for crop growth and nutrition across climatic and soil gradients are little understood.

In general, an increase in soil fertility is positively associated with greater quality and nutrient concentrations of organic amendments (Vitousek and Sanford, 1986). The quality of organic inputs in terms of N, lignin and polyphenols influence the rate of decomposition of organic inputs (Palm et al., 2001). Labile materials (often also labeled high quality) decompose rapidly and are associated with a rapid and large release of plant nutrients. In contrast, organic amendments high in lignin or polyphenols (low quality) may first immobilize soil nutrients and subsequently release it gradually for crop demand (Palm, et al., 2001). As an extreme of a stable amendment, biochar decomposes very slowly and typically adding few nutrients (with the exception of K and some other nutrients in high-ash biochars) but also not immobilizing N or P in contrast to crop residues (Cheng et al., 2012). In addition, nutrient release and availability is contingent on the rate of decomposition as a function of moisture, temperature, mineralogy and soil texture (Sanchez et al., 1989) as well as quality of organic inputs.

The main objective of this study was to examine the importance of nutrient additions and stability of organic matter additions along a wide environmental gradient for increasing maize production under CF. We investigated the effects of readily decomposable organic additions in contrast to stable organic additions on crop yield and nutrition as influenced by (i) environmental variables such as rainfall, (ii) soil texture and, (iii) slope position. We hypothesized that addition of stable organic matter such as biochar increase yields to a higher degree under high than low rainfall while the easily decomposable organic matter increase yields to a higher degree under low rainfall than high rainfall. Phosphorus uptake would decrease with higher rainfall without inorganic additions and that biochar would have a greater effect on P uptake with higher rainfall.

2. Materials and methods

2.1. Study site description

We conducted on-farm experiments distributed along a transect from Mambwe, Lundazi and Mpika districts of Eastern and Northern provinces in Zambia within Universal Transverse Mercator projection (UTM) Zone 36S (11° 51′ S to 13° 30′ S latitude, 31° 25′ E to 33° 07′ E longitude). These locations covered a wide environmental gradient of mean annual temperatures ranging between 10°C and 35°C with elevation ranging from 500 to 1400 m above sea level (Table 1). The sites are located in the sub-humid tropics with mean annual precipitation lying between 500 mm to 1250 mm with a unimodal distribution pattern from November to April. The area was selected on a physiographic basis which is partitioned into three agroecological zones (AEZ) (Chiwele and McKenzie, 1996) differentiated by rainfall pattern and soil type (Table 1). Over 280 small-scale farmers with less than 2 ha of land and practicing conservation farming (CF) were selected (for locations, see supplementary information) from the three AEZs. Sites were stratified according to mean annual precipitation, soil texture and slope position to ensure representation of the most important environmental characteristics.

AEZ I soils are classified as Haplic Luvisols (FAO, 1973) in the Rift troughs and Haplic Solonetz (loamy and clayey soils with coarse to fine loam top soils) on flat land and have a higher pH and nutrient content than other AEZs (Table 1). Rainfall in this zone is low, early, and erratic with a cumulative average of 796 mm during the cropping season. AEZ II has a degraded plateau with moderately leached clayey to sandy-loam soils classified as Haplic Luvisols, Haplic Acrisols and Haplic Lixisols, with an average cumulative rainfall of 900 mm. Soils in this zone have coarser texture, lower nutrient and carbon (C) contents than in the other two AEZs (Table 1). Soils in AEZ III are highly weathered and leached with clayey to loamy textures and are classified as Haplic Acrisols, with the lowest pH and CEC (Table 1) indicative of a mineralogy dominated by highly weathered clays. AEZ III has the greatest cumulative rainfall with 1045 mm, which starts later and has more even rainfall distribution.

Table 2.1. Physical and chemical characteristics of soils and environmental co-variates across the three agroecological zones

Location	AEZ I			AEZ II			AEZ III		
	Mean	SD†	CV‡	Mean	SD	CV	Mean	SD	CV
Dominant soil taxon	Haplic Luvisol, H.Solonetz			Haplic Luvisol, H. Acrisol, H. Lixisols			Haplic Acrisol		
Elevation, m a.s.l	556	9.0	6201	977	190.2	419	1394	15.3	9087
Rainfall, mm yr^{-1}	575.5	193.0	298	796.1	354.2	225	1371.2	544.3	252
Slope gradient, degrees	0.36	0.2	190	1.51	0.8	180	1.78	1.3	134
Soil properties									
Silt + clay, %	47.8	22.3	46.7	23.7	9.1	38.5	52.6	20.8	39.6
pH (KCl)	6.0	0.5	7.7	5.8	0.5	7.8	5.0	0.4	8.5
Total C, g kg^{-1}	18.5	39.4	47.0	8.9	4.6	51.8	17.9	0.4	8.5
Total N, g kg^{-1}	1.3	3.0	43.0	0.6	0.3	43.8	1.1	9.7	54.3
CEC, mmol kg^{-1}	318.3	157.0	493.2	187.3	162.0	864.8	101.8	65.2	639.9
Available nutrients									
Total P mg kg^{-1}	21.4	10.9	196.0	14.4	6.3	230.0	21.4	27.7	77.0
Ca, mmol kg^{-1}	22.5	9.3	41.5	7.4	5.6	75.9	9.0	5.0	55.3
Mg, mmol kg^{-1}	8.1	5.9	72.4	1.9	3.9	206.2	3.0	1.4	45.6
K, mmol kg^{-1}	2.6	4.4	169.6	0.9	4.0	469.6	0.3	0.3	72.7
Na, mmol kg^{-1}	1.0	4.6	441.0	0.5	4.1	788.5	0.1	0.1	85.6
Fe, mg kg^{-1}	73.8	24.6	33.4	32.8	9.9	30.2	28.5	8.4	29.6
Cu, mg kg^{-1}	52.9	18.7	35.3	55.4	25.2	45.5	36.9	17.6	47.7
Mn, mg kg^{-1}	1.5	4.5	296.3	0.7	4.4	605.3	1.2	0.9	72.6
S, mg kg^{-1}	9.5	7.4	77.5	2.8	5	182.3	1.6	3.8	238.2

Source: *Lusaka Meteorological station: MAT Mean annual temperature: MAP Mean annual precipitation: †SRTM-DEM from CGIAR-CSI: ‡ SD, Standard deviation: # CEC, cation exchange capacity: § CV, coefficient of variation (ratio of SD and mean)

2.2. Field layout and experimental treatments

Farms along a wide environmental gradient of mean annual precipitation, terrain and soil texture variability were identified that practiced CF. Soil texture and terrain variables were comparable across the rainfall gradient, but significantly varied within each Agroecological Zone (AEZ) (Table 1). The experimental design was stratified with repeated measures and treatments assigned at farm level. Stratification was implemented based on a three-level model to examine the effects of environmental variables. To ensure equal representation, 45 strata were determined based on (i) mean annual precipitation (MAP) (three AEZs); (ii) five slope positions' and (iii) soil texture (fine, moderate and coarse clay content). Within each stratum, six farms were randomly chosen and harvest measurements taken on each five CF treatments.

In order to arrive a better understanding of whether and when CF is appropriate for smallholder farming, and to search for better ways of tailoring CF to farmers' needs, we combined CF with the following organic and inorganic nutrient additions along the described environmental gradients: (i) a control, CF with farmer inputs managed and practiced; (ii) *Gliricidia sepium* (Jacq.) Steud. leaves (hereafter gliricidia); (iii) cow manure (hereafter manure); (iv) manure with fertilizer (hereafter fertilized manure); and (v) biochar with fertilizer (hereafter biochar). The application rates for the three organic amendments (manure, gliricidia and biochar) were approximately 0.4 tons C ha^{-1} (Table 2) with a rate of 6 t C ha^{-1} of the basin area (about 7% of the total area). Inorganic fertilizer compound D (10 NH_4O_4 :20 P_2O_5 :10 K_2O) was applied with N at 200 kg N ha^{-1}, K at 100 kg K ha^{-1} and P at 100 kg P ha^{-1} in quantities that likely made nutrients not limiting plant growth and assimilate potential achievable yield. Lime was applied at 200 kg ha^{-1} and micronutrients sulfur at 6 kg S ha^{-1}, zinc 1.4 kg Zn ha^{-1} and boron at 1 kg B ha^{-1}.

The plots were established on present one-year-old CF fields with maize as a preceding crop. The trials were conducted during the cropping seasons of 2006/2007 and 2007/2008, but only the last season is presented here. Plots had a dimension of 4.5 m by 3.5 m each (with approximately 22-25 planting basins) and were planted in rows with a distance of 0.9 m and 0.7 m within each row, and an interplot spacing of 2 m. The choice of maize variety was made by farmers. Maize was planted at a rate of 20-25 kg of seeds per hectare using four seeds per planting hole and thinned to three (Aagaard and Gibson, 2003a, 2003b).

2.3. Organic material selection

Gliricidia, manure and biochar were used in this experiment as organic C sources. The choice of these organic materials was based on their contrasting qualities especially the C/N ratio and C stability (Table 2). Gliricidia is a labile organic matter (OM) which has a low C/N ratio and decomposes very rapidly releasing large amounts of N, P and K (Palm and Sanchez, 1990; Mafongoya et al., 1998). Biochar was chosen for its recalcitrance to decomposition (Schmidt and Noak, 2000), ability to increase cation exchange capacity (CEC) (Tryon 1948; Lehmann and Rondon, 2006) and as an extreme end member of its high stability. Animal manure is a soil amendment used by smallholder farmers which, because of variability in quality, does not generally conform to a decision guide (Murwira et al., 2002; Markewich et al., 2010). The quality of manure is intermediate between gliricidia and biochar and therefore complements the wide range of different OM qualities. The three organic materials therefore will have differing impact on the soil organic C (SOC) due to their differing C/N ratios.

2.4. Trial management

Collection of gliricidia leaves was done by hand at Dunavant cotton farm in Chipata. Manure was acquired from an individual local farmer. Manure management before incorporation into soil included heap storage in an open *kraal*, as is the local practice among many Zambian smallholder farmers. Biochar was produced from rice husks using a traditional kiln method whereby rice husks were piled in a mound with a height of 0.8 m, and then covered with soil allowing thermal decomposition under oxygen-deprived conditions at a temperature between 400 – 500^{o}C (estimated from Schenkel et al., 1998). All the organic and inorganic materials were applied directly into the planting basin at a depth of 0.15 m and covered with soil up to 0.10 m.

For the treatments receiving a combination of organic and inorganic fertilizers, 57% of N obtained was applied as basal dressing and the remaining portion of N was obtained from urea (46% N) as top dressing. Application of urea was made following the recommended farmer's practice six weeks after planting. Sufficient weeding was done for the first six to eight weeks of growing. After harvesting, the maize stovers were retained in the experimental plots, as part of the CF practice of residue retention to maintain over 30% ground cover (Hobbs, 2008).

Table 2.2. Properties of organic amendments and annual application rates.

Organic amendment	Mass $t\ ha^{-1}$	C $t\ ha^{-1}$	N $kg\ ha^{-1}$	C/N ratio	P $kg\ ha^{-1}$	C/P ratio	K $kg\ ha^{-1}$	pH
Gliricidia	0.95	0.4	35	12	1.4	288	22	8
Biochar	0.54	0.4	3.3	107	0.2	2218	1.5	9.4
Manure	1.43	0.4	29	18	5.6	192	33.2	9.4
Compost	0.2 - 0.5	0.1	16	35	0.9	454	2.2	–

2.5. Determination of site characteristics

For site characterization, real-time daily rainfall was collected and recorded throughout the cropping season on each farm by farmers using a rain gauge. Soil properties were determined by taking ten random topsoil samples before any amendments were added, from the area of the plots on each farm at a depth of 0.15 m and pooled as a composite. From the bulked composite, sub-samples were air dried and passed through a 2-mm sieve. Sieved samples were analyzed for pH (in KCl) at the w/v ratio of 1:2.5 using a glass electrode. Available P and Ca, Mg and K were analyzed using the Mehlich 3 (Mehlich, 1984) extraction procedure. Soil extracts were analyzed for Ca, Mg, K and P on an Inductively Coupled Plasma spectrometry (ICP, Spectro Ciros, Spectro A.I. Inc. MA, USA).

In order to estimate the cation retention independent of soil pH, potential cation exchange capacity (CEC_{pot}) was determined by quantifying NH_4 exchanged with 2 N KCl after saturating cation exchange sites with NH_4-Ac buffered at pH 7.0 (Anderson and Ingram 1993; Hendershot et al. 1993), followed by colorimetric NH_4 analysis on a continuous flow analyzer (Technicon Auto Analyzer, Colorimeter; Technicon, NY, USA). A smaller subsample of 0.5 g of each soil sample was ground further into fine powder for 10 min with a ball mill (Retsch® MM301, Retsch Inc, Newton PA, USA). From the fine material only 20-mg sample was weighed into Sn capsules and analyzed for total C and N contents with a Europa ANCA-GSL CN auto-analyzer (PDZ Europa Ltd., Sandbach, UK).

2.6. Terrain parameters

Digital elevation models (DEM) generated from the Shuttle Radar Topographic Mission (SRTM; CGIAR-CSI) at a 90-m resolution were utilized to derive slope gradient, slope curvatures (profile, plan, absolute) and slope aspect (slope direction) . Geographic coordinates and elevation values of individual fields were taken and recorded using Garmin 72XL model GPS instrument when conducting baseline site characteristics. These attributes were used to acquire field-observed values and to validate the DEM-derived parameters. Elevation values recorded with GPS (m) and values derived from SRTM DEM at 90 m correlated significantly (R^2=0.99; $P<0.0001$).

The SRTM-derived terrain parameters were computed using ArcGIS 9.3 using a standard window of eight pixels surrounding each pixel. Slope gradient in arc-degrees and slope curvature were derived using the surface tool in Spatial Analyst Toolbox of Arc GIS (ESRI, Redlands, CA). This process utilizes a eight pixel window around the processing or center pixel (3 x 3 pixel array) and the average maximum technique to calculate slope gradient values. This does not consider the characteristics of the upslope contributing area or relative position of individual pixels (ESRI, 1996). Slope gradient quantifies the rate of elevation change, defined as the first-order derivative of the terrain. Plan and profile slope curvature describes the shape of the terrain and acceleration or deceleration of water flow over a surface. Negative curvature corresponds to concave surface, while positive curvature corresponds to convex surfaces or hills in plan curvature and vice versa in profile curvatures. Zero values have no slope curvature. For this study we use value of absolute curvature which combines both profile and plan curvatures. Slope aspect (azimuth) was computed in units of arc degrees, recorded through the cosine function from north, and classified into four degrees categories: -1 represent south (135-2250); -0.5 represents west (225-3150); 0.5 east (45-1350); and 0 representing north (315-450)] after cosine transformation. Table 1 shows the elevation and slope data for the region. To validate quantitative from DEM terrain parameters, a value was computed for the center of individual plot based on four GPS coordinated at the corners of individual plot.

2.7. Field sample collection

Maize grain and above ground biomass (stover and core) were determined in all plots at harvest at physiological maturity. Stover and grain yield were measured on subplots of 4.5 m by 3.5 m. To avoid edge effects one row and one plant at the end of each row was removed. This gave a net harvest area of 5.7 m^2. Fresh plant materials were weighed and a representative subsample dried at 60°C for 48-72 hours and then re-weighed. An aliquot grain subsample of about 500 g was taken for moisture content determination using a PreAgro grain moisture tester (PreAgro 35 Oy Santasalo-Sohlberg, AB; Finland) in order to check whether grain had attained 13% moisture content after which yield measurements were corrected to a moisture content of 15.5%. In less than 4% of the cases where cobs were missing from the subplot (removed by people or destroyed by elephants), the average weight of the grain per harvested cob was multiplied by the measured plant density at harvest to obtain an estimate of the grain yield. The geographic coordinates of the sampling points were taken and recorded with a handheld global positioning system (GPS;

Garmin 72XL model, instrument precision of ±10 ft) using Universal Transverse Mercator (UTM, Zone 36) (for locations see supplementary information).

2.8. Nutrient uptake

Nutrient uptake by maize was determined by analyzing N, P, K, Ca, and Mg in a composite sample of the entire biomass at harvest (this includes maize cob, stover, and grain). Subsamples were oven dried at 60°C for 48–72 h (until constant weight was attained) and finely ground for wet digestion with 70% nitric acid and 30% hydrogen peroxide on a heating block (Oliva et al., 2003) until a white-colored residue was obtained. Tissue concentrations of nutrients P, K, Ca, and Mg were determined by Inductively Coupled Plasma (ICP, Spectro Ciros, Spectro A.I. Inc. MA, USA) spectrometry. Total nutrient uptake was calculated as the product of yields (maize cob, stover and grain) and the proportion of tissue concentrations. Total N and C was determined by dry combustion after fine grinding plant using a Cyclotec Sample Mill Tecator (model 1093, American Instrument Exchange, Inc., USA).

2.9. Statistical analysis

Statistical analysis was conducted using three level models since treatments were nested within farms. The statistical differences between experimental treatments and between agroecological zones were determined by Analysis of Variance (ANOVA) using JMP system (SAS Institute Inc.; Cary, NC). Treatment means were separated using standard error of difference. The soil chemical and physical properties and sites characteristics were used as environmental co-variates.

Principal component analysis (PCA) was employed to avoid problems of multicollinearity among the 21 groups of soil, environmental co-variates and terrain variables. PCA as a method of factor extraction was applied for it needs no prior estimates of the amount of variation of each soil, environmental and terrain variables that will be explained by these components. Further, PCA is able to derive linear combinations of a set of variables that retain most of the information and variation contained in the variable data set. Only factors with eigenvalues >1 were retained (Kaiser's criterion) (Kaiser, 1960) and rotated orthogonally with varimax option. Rotation of factors is fundamentally the application of linear transformation to achieve more meaningful and discriminating patterning of variable factor loadings within and between factors (Hair et al., 1987). Correlation coefficients were calculated among the identified PCs on crop yield and total nutrient uptake.

3. Results

3.1. Grain yield and total dry matter production

Average maize grain yield along the environmental gradient varied with different amendments from 1.0 to 5.8 t ha^{-1} while above ground biomass growth averaged between 2.1 to 10 t ha^{-1} (Table 3). In all sites, applied full inorganic fertilization with biochar and manure significantly increased yields ($P<0.05$) by 2.7, 2.9 and 2.2 t ha^{-1} in comparison to control, gliricidia and manure, respectively (Table 3). Similar observations were made for total above ground biomass with full fertilization treatments being significantly higher than in control, gliricidia and manure treatments (Table. 3). Average grain yield with manure additions were significantly ($P<0.05$)

higher than those with gliricidia additions and in the control. Overall, absolute increase in grain productivity by organic additions was greater in the wetter (R^2=0.71; $P<0.05$) than the drier regions (AEZ I).

Fertilizer additions to biochar and manure in degraded plateau locations produced the highest effect ($P<0.0001$) with relative yield increases of 320% and 300%, respectively (Fig. 1), while manure and gliricidia applications had the lowest effect with relative yield increase of 46% and 24%, respectively (Fig. 1). In contrast, manure (P=0.3) and gliricidia (P=0.01) in the drier region (AEZ I) had the highest percent yield increase relative to control of 86% and 61%, respectively, compared to other AEZs (Fig. 1). Biochar additions in moderately degraded plateau had significantly (P=0.03) higher yield increase relative to control than in the drier region while gliricidia additions had significantly (P=0.008) greater relative yield increases in the drier than wetter region.

Table 2.3. Maize yield and above ground biomass with different organic and inorganic amendments under conservation farming (CF) during 2007/208 cropping season (means followed by standard error in brackets; values followed by the same letter in the same column are not significantly different at P<0.05; n=284 for all sites).

	Grain yield (t ha^{-1})				Above ground biomass‡ (t ha^{-1})			
Treatment	AEZ I	AEZ II	AEZ III	All Sites	AEZ I	AEZ II	AEZ III	All Sites
Control	1.4 c (0.2)	1.0 bc (0.1)	1.4 c (0.3)	1.3 c (0.1)	4.0 b (0.3)	2.3 b (0.3)	5.1 b (0.6)	3.3 b (0.3)
Gliricidia	1.1 c (0.2)	0.9 b (0.1)	1.3 c (0.3)	1.1 c (0.1)	4.4 b (0.3)	2.1 b (0.3)	3.7 b (0.5)	3.4 b (0.7)
Manure	2.2 b (0.2)	1.3 c (0.1)	2.5 b (0.3)	1.8 b (0.1)	4.3 b (0.3)	2.1 b (0.3)	4.4 b (0.6)	3.2 b (0.2)
Manure + Fertilizer	4.1 a (0.2)	3.5 a (0.1)	5.7 a (0.1)	4.0 a (0.1)	6.6 a (0.3)	5.5 a (0.3)	10.0 a (0.6)	6.5 a (0.2)
Biochar + Fertilizer	3.8 a (0.2)	3.5 a (0.1)	5.8 a (0.3)	3.9 a (0.1)	6.4 a (0.3)	5.7 a (0.3)	9.9 a (0.6)	6.5 a (0.2)
P value (0.05)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Observations	94	158	32	284	94	158	32	284

‡ Excludes grain yield

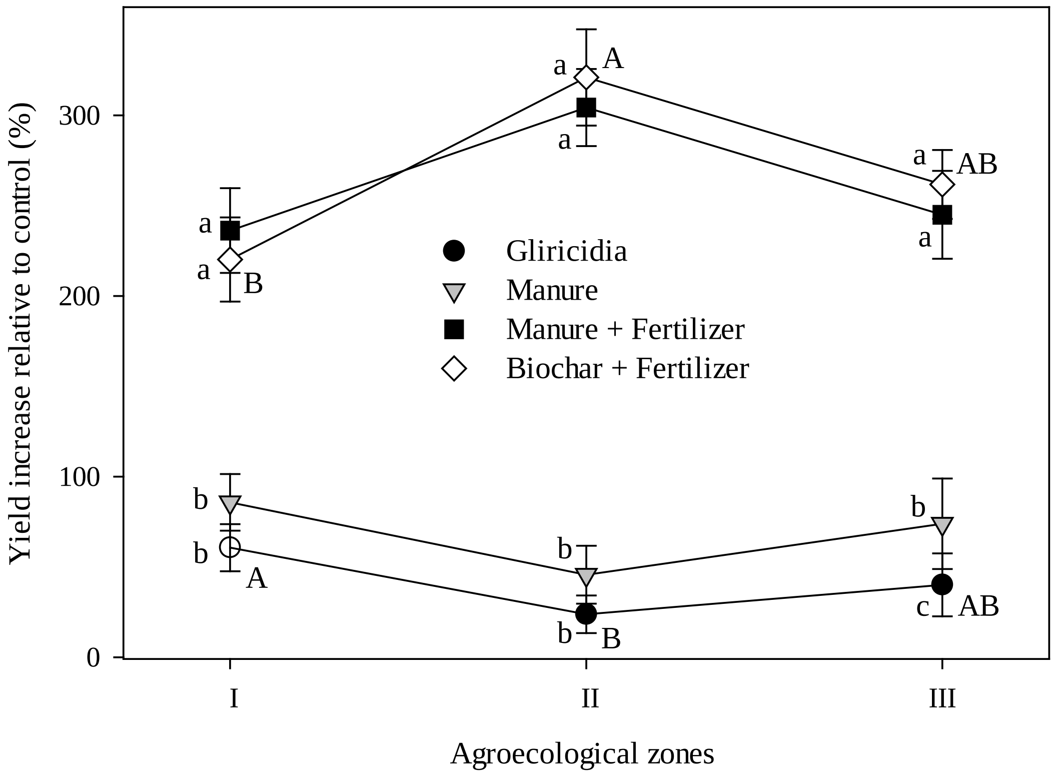

Figure 2.1. Maize grain yield expressed as the percent yield increase relative to control across the three agroecological zones in Zambia (means and standard errors; n=284). Symbols with different letters (capital letters) within a treatment are significantly different at *P*<0.05 (symbols not shown if no difference). Symbols with different letters (small caps) within AEZ are significantly different at *P*<0.05.

3.2. Relationship between grain yield with soil properties and environmental co-variates

Univariate analysis of some soil properties tended to correlate with crop yields. Productivity was increasingly responsive to additions of inorganic fertilizer as mean annual precipitation increased. Addition of inorganic fertilizer together with stable organic matter (OM) biochar and labile manure significantly ($P<0.01$) increased grain yield with greater total soil C, N, available P and basic cations (K, Ca, Mg, Na) in individual AEZs as well as all sites combined. For biochar additions, productivity increased with increase in silt-clay ($P=0.02$) and declined with greater total soil C ($P=0.05$) and N ($P=0.03$) in wetter region (Fig. 2b, c & d), while on the degraded plateau, productivity decreased ($P=0.006$) with higher pH values (Fig. 2a).

In contrast, labile additions of manure with inorganic fertilizer significantly increased grain yield with increases in rainfall ($P=0.003$) and elevation ($P=0.01$) in the degraded plateau (Fig. 3c & d). With additions of labile manure but without inorganic fertilizers, grain yield correlated significantly ($P=0.01$) with increase in total soil C and N across all sites. Slope curvature values ranged between -0.205 to 0.131, -0.15 to 0.08 and -0.067 to 0.071 for absolute, plan and profile respectively along the environmental gradient. Sole manure additions increased productivity ($P=0.03$) with increasing slope gradient (Fig. 3b) while grain yield of the control increased with slope aspect ($P =0.01$, in north facing slope direction) in the wetter regions only (Fig. 3a).

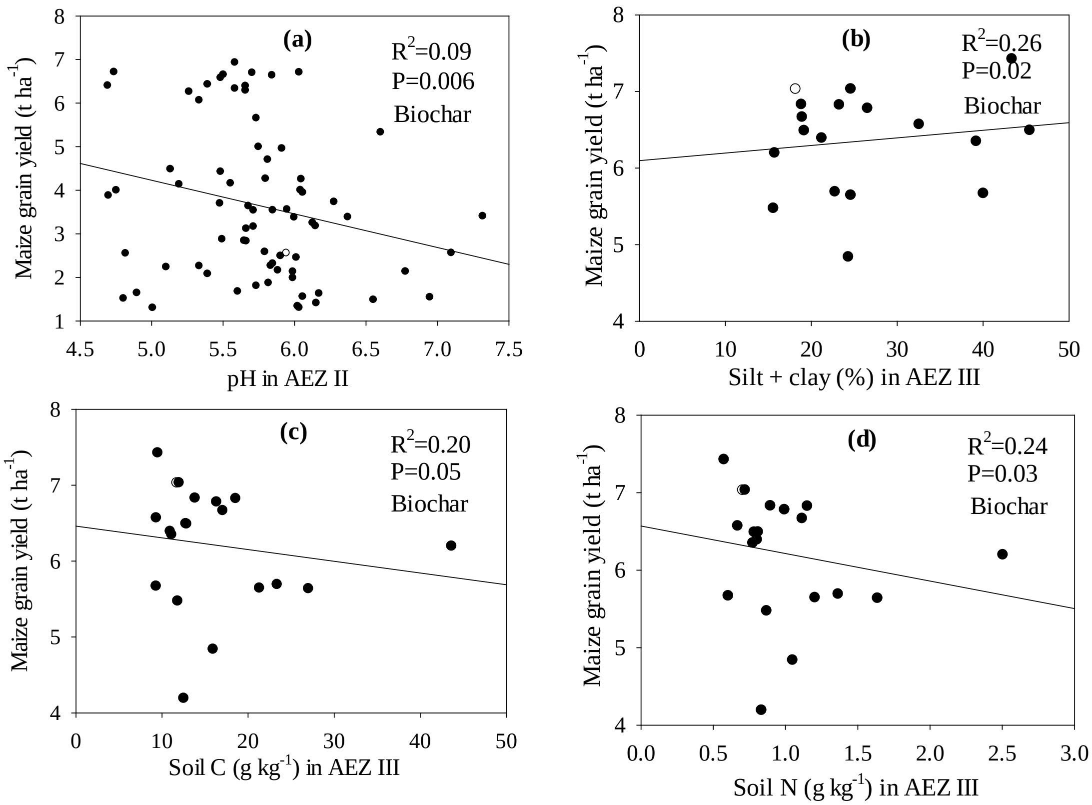

Figure 2.2. Influence of soil properties (a) pH in AEZ II, (b) texture, (c) soil C and (d) soil N, all in AEZ III on maize grain yield with biochar + fertilizer additions.

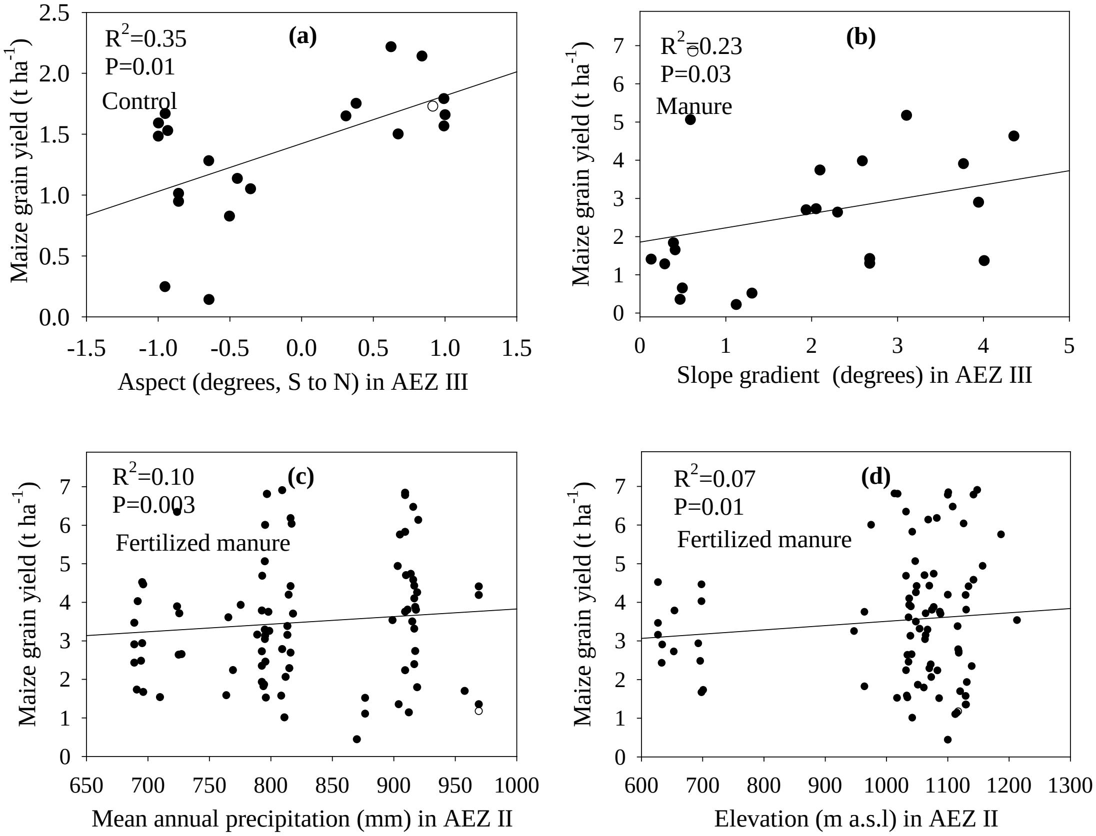

Figure 2.3. Influence of environmental co-variates on maize grain yield with additions of (a) control on aspect (slope direction) and (b) manure on a slope gradient both in AEZ III; fertilized manure with (c) mean annual precipitation and (d) elevation both in AEZ II.

3.3. Plant nutrition and nutrient uptake

Four treatments (control, manure, fertilized manure and biochar) were selected for further investigation of their influence on total plant nutrient concentrations (Table 4) and total plant nutrient uptake (Table 5). Nitrogen concentrations in total plant were about 1.5 g kg^{-1}, 1.3 g kg^{-1} and 2 g kg^{-1} above the levels of manure treatment with addition of fertilizer in AEZ I, II and III, respectively (Table 4). In contrast, concentrations of K, Mg and Ca in total plant was significantly higher when adding manure than fertilized manure and ranged from 0.1 g kg^{-1} to 0.5 g kg^{-1} along the environmental gradient. Sole manure additions improved N, K, Ca and Mg but not P concentrations in the drier area, whereas neither N or P but only K, Ca and Mg concentrations increased in the wetter region. Addition of inorganic fertilizer in the drier region only increased N concentrations. However, fertilizer additions to manure in the wetter region improved both N and P concentrations.

Addition of stable biochar improved P, K, Ca and Mg concentrations to a greater extent compared to manure additions both with fertilizer in the degraded plateau than in drier and wetter regions. Biochar additions improved P concentrations but not N, K, Ca and Mg in the drier area, while N concentrations declined and no changes in P concentrations were observed in the wetter region. Potassium and Mg concentrations increased with biochar additions in comparison to manure where both received fertilizer in the wetter region. However, K concentrations in the wetter region were lower than in other AEZs.

As a result of organic and inorganic additions, the total plant uptake of N, P, K and Mg in all treatments was superior in wetter regions than drier regions, while the degraded plateau (AEZ II) had the lowest uptake. Total N uptake increased by 36.7 kg ha^{-1}, 47.3 kg ha^{-1} and 84 kg ha^{-1} above the levels of manure additions when additional full fertilization was applied in AEZ I, II and III, respectively (Table 5). In the degraded plateau, recalcitrant biochar showed a significantly greater uptake (P=0.05) of P, K, Ca and Mg (0.8 kg ha^{-1}, 1.59 kg ha^{-1}, 0.32 kg $ha^{-1}$and 0.99 kg ha^{-1} respectively) than fertilized manure while similar increases in K (1.43 kg ha^{-1}) and Mg (0.8 kg ha^{-1}) uptake were observed in wetter regions. Nitrogen, P, K and Mg uptake in the unamended control was significantly higher than with manure additions in wetter regions while P uptake was greater in the degraded plateau and the driest region.

3.4. Relationship between total plant uptake and environmental co-variates

Environmental co-variates such as mean annual precipitation, elevation, slope gradient and slope aspect significantly affected nutrient uptake. Nutrient uptake trend increased towards north and south facing slopes and decreased with east facing slopes in all sites (Supplementary Table 1b). Control plots also had significant higher Ca (P=0.05) nutrient uptake in north than south facing slopes in wetter and degraded plateau than drier regions.

Table 2.4. Nutrient concentration in the total above ground biomass as a function of environmental gradient.

Agroecological Zones	Treatment	Nutrient concentrations in total above ground biomass ($g\ kg^{-1}$)				
		N	P	K	Ca	Mg
AEZ I	Control	9.93	2.58	6.04	0.49	1.06
	Manure	11.55	2.44	6.66	0.89	1.28
	Manure + Fertilizer	12.9	2.36	6.18	0.53	1.03
	Biochar + Fertilizer	10.99	2.49	5.83	0.48	1.01
AEZ II	Control	9.83	2.89	6.74	0.48	1.24
	Manure	12.27	2.65	6.74	0.62	1.38
	Manure + Fertilizer	13.58	2.47	6.58	0.57	1.11
	Biochar + Fertilizer	11.12	2.65	6.94	0.62	1.31
AEZ III	Control	12.33	1.96	4.86	0.47	1.11
	Manure	11.87	1.87	5.51	0.64	1.27
	Manure + Fertilizer	13.89	2.05	5.1	0.48	1.11
	Biochar + Fertilizer	13.49	2.05	5.38	0.4	1.23
	$LSD_{0.05}$	0.17	0.05	0.13	0.02	0.02
	P value $_{0.05}$	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Table 2.5. Nutrient uptake in total above ground biomass as a function of environmental (rainfall) gradient.

Agroecological Zones	Treatment	Nutrient Uptake (kg ha^{-1})				
		N	P	K	Ca	Mg
AEZ I	Control	40.48	10.01	23.59	1.86	4.08
	Manure	50.56	9.98	26.67	3.73	5.06
	Manure + Fertilizer	87.27	16.20	42.05	3.52	6.96
	Biochar + Fertilizer	73.33	16.36	38.00	3.08	6.53
AEZ II	Control	23.85	6.26	13.88	0.97	2.52
	Manure	26.06	5.35	14.23	1.27	2.94
	Manure + Fertilizer	73.33	13.09	34.36	2.84	5.80
	Biochar + Fertilizer	59.85	13.89	35.95	3.16	6.79
AEZ III	Control	64.86	10.67	26.37	2.41	5.86
	Manure	56.18	8.79	25.06	2.70	5.66
	Manure + Fertilizer	140.15	21.35	51.85	4.85	11.35
	Biochar + Fertilizer	132.38	20.24	53.28	4.02	12.15
	$LSD_{0.05}$	2.50	0.51	1.21	0.26	0.24
	P value $_{0.05}$	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

3.5. Relationship between site characteristics and crop yield and nutrient uptake

Principal Component Analysis (PCA) was performed to group correlated dominant soil properties, environmental co-variates and terrain variables to the smallest possible subsets representing the majority of variation. Although some of the PCs identified were similar between regions and in all sites along the environmental gradient, several were different. Soil fertility, texture, pH and curvature factor were identified as common PCs (factors) that influenced yield and total plant nutrient uptake along the gradient and individual AEZ (Table 6). Of possible 21 variables, PCA identified seven principal components (PCs) with eigenvalue >1 (Table 7) which were retained to better understand the relationship with yield and nutrient uptake for all sites. These PCs cumulatively explained 80% of the total sample variance, suggesting that seven PCs adequately explain variation. Measured variables with relatively high PC loadings (>0.65) within each factor are indicated on Table 7. These highly loaded variables were then used to propose possible common underlying factors that linked variables together within each PC. In this study, all measured variables in the analysis are retained.

PC1 had the largest eigenvalue and most variables with large positive loadings (Table 7). It had high positive loadings (>0.80) for C, N, Mg, Ca and Mn, and moderate K loadings. It was termed as *soil fertility factor* because organic matter and base cations are indicators of soil fertility. PC2 was termed as *rainfall* because of absolute dominant positive loadings for rainfall (correlated to elevation) and high negative loadings for Fe and moderate negative loadings for K and slope aspect. PC3 was termed as *curvature factor* because of absolute dominant positive loadings for absolute and plan curvature, and dominant negative loadings for profile curvature. Relatively large positive and negative curvatures occur in areas of transition on hillslopes and these areas either lose or accumulate soil through erosive processes. Thus, areas with convex curvature lose soil and have shallow A horizons and areas of concave curvature accumulate and have deep A horizons. PC4 was termed as *texture factor* because high loadings in S, Na and silt-clay. Sulfur and Na are closely related to soil physical properties and aggregation, while silt-clay is a measure of particle size distribution. PC5 and PC6 were regarded as *slope gradient* and *pH factors*, respectively, because of absolute dominant high positive loadings in slope gradient and pH, while PC7 was termed as *Soil P factor* because of relatively higher positive loadings of P than Zn. More so, Zn is usually the first element to be limiting crop growth when soil P nutrition is high.

Table 2.6. Common factors derived from principal components analysis (PCA) identified for all sites and individual agroecological zones.

AEZ	Principal Components†						
	PC1	PC2	PC3	PC4	PC5	PC6	PC7
All sites	Soil fertility	Rainfall	Curvature	Texture	Slope gradient	pH	Soil P
I	Soil fertility	Texture	Curvature	pH	Aspect	Soil P	Soil Zn
II	Soil fertility	Curvature	Texture	Micro-nutrients	Slope gradient	pH	n/a‡
III	Soil fertility	Curvature	Soil chemistry	Rainfall	Texture	pH	Soil Fe

† PC 1 up to 7 with eigenvalues >1 as identified by PCA (from Table 7; S2a , b and c). ‡ n/a, not applicable (no eigenvalue with >1).

Table 2.7. Rotated loadings of measured soil properties, site variables and environmental co-variates in all sites for the seven factors identified with principal component analysis with eigenvalues >1.0.

Variables	Soil fertility PC1	Rainfall PC2	Curvature PC3	Texture PC4	Slope gradient PC5	pH PC6	Soil P PC7
Eigen value	7.05	2.78	2.23	1.40	1.21	1.13	1.09
Variance	4.7	3.2	2.6	2.3	1.4	1.3	1.3
Cum Percent	22.4	37.8	50.4	61.4	68.2	74.3	80.4
pH	0.16	-0.04	0.00	-0.01	-0.07	**0.85**	-0.04
Silt-clay	0.00	-0.09	-0.02	**0.67**	-0.21	-0.06	0.28
N	**0.92**	-0.10	0.05	0.17	-0.11	0.05	0.10
C	**0.93**	-0.02	0.07	0.08	-0.10	0.02	0.08
Ca	**0.80**	-0.43	-0.04	0.15	-0.18	0.19	0.06
P	-0.06	-0.17	0.07	0.03	-0.07	0.21	**0.77**
Mg	**0.82**	-0.39	-0.07	0.12	-0.20	0.18	0.05
K	**0.55**	**-0.55**	-0.05	0.34	-0.25	0.20	0.16
Na	0.48	-0.25	-0.06	**0.75**	-0.10	0.06	-0.07
Fe	0.48	**-0.67**	-0.15	0.17	-0.38	0.04	0.10
Zn	0.24	0.10	0.07	0.09	0.13	-0.29	**0.67**
Mn	**0.81**	0.20	0.07	0.05	0.26	-0.02	-0.10
Cu	0.10	-0.09	0.14	**0.52**	0.17	0.47	0.22
S	0.18	-0.29	-0.05	**0.83**	-0.07	-0.03	-0.15
Rainfall	-0.05	**0.91**	0.07	-0.17	-0.09	-0.16	-0.04
Elevation	-0.27	**0.92**	0.06	-0.19	-0.10	-0.07	-0.04
Slope gradient	-0.18	0.00	-0.03	-0.19	**0.95**	-0.02	0.04
Aspect	-0.10	**-0.47**	0.15	0.09	-0.09	-0.25	-0.01
Curvature	0.02	0.02	**0.99**	-0.01	-0.01	0.00	0.04
Curvature profile	-0.07	-0.08	**-0.89**	0.07	0.06	0.04	-0.07
Curvature plan	-0.02	-0.05	**0.87**	0.03	0.07	0.05	0.02

3.5.1. Combined analysis of all sites

Retained PCA in all sites were correlated to yield and total nutrient uptake. Significant correlations were observed between four PCs and yield (Table 8) as well as five PCs and total nutrient uptake (Table 9). Maize yields in control plots correlated positively (P=0.01) with soil fertility (PC1) and with texture (PC4) at P=0.001). Crop yields after manure additions were positively correlated with soil fertility (P=0.001) and texture (P=0.02). Yields with additional inorganic fertilizer correlated significantly with rainfall (PC2) (P=0.02), texture (P=0.02) and soil P (P=0.02). Yields after additions of biochar showed positive correlations with rainfall (P=0.0004) and higher yields with concave slopes (negative curvature, PC3) (P=0.05). Notably, texture significantly correlated with yields after additions of manure (P=0.02) or manure with fertilizer (P=0.02); and highly with the control (P=0.001) but not with yields after biochar additions.

Five of the seven site and soil properties correlated significantly with total plant nutrient uptake in all sites. Two factors significantly contributed to nutrient uptake in control (Table S3a). Soil fertility (PC1) improved maize N, P, K, Ca and Mg uptake (P=0.05), while texture improved P, K, Ca and Mg uptake. When labile manure was applied, soil fertility improved (P=0.01) N, P, K, Mg but not Ca uptake, while pH improved (P=0.01) P and Mg uptake. Further, convex slopes indicative of shoulders or summits (i.e., higher curvature) decreased P uptake (P=0.05). Addition of inorganic fertilizer to both manure and biochar improved crop uptake of N and Mg (P=0.05) with greater rainfall. But only after biochar additions, a higher pH decreased N uptake and convex slopes on shoulders and summits decreased N, P, K and Mg uptake (P=0.05).

3.5.2. Analysis by agroecological zone

When restricting the analysis to the driest region (AEZ I), a finer texture still improved yield in the control (P=0.03), but not nutrient uptake (Supplementary Table S3a). In contrast, both inorganic fertilization regardless of organic amendment, improved P, K, Ca and Mg uptake (P<0.05) in concave slopes indicative of foot slopes and valleys. Additions of fertilized manure improved uptake of Ca with higher pH (P=0.05), however Ca uptake decreased with higher soil fertility (P=0.04). In contrast, addition of recalcitrant biochar increased P, K, Ca and Mg uptake with lower soil fertility (P<0.05). Further, additions of biochar increased K uptake with higher pH (P=0.02) and in north facing slopes (P=0.01), however greater soil P (P=0.03) and finer texture (P=0.02) decreased K uptake.

In the degraded plateau, only yields with biochar additions were increased in concave-slope positions (i.e., lower curvature, PC2, P=0.04) and with lower soil micronutrient contents (P=0.03). Flatter areas improved K (P=0.02) and Mg (P=0.02) uptake when only manure was added.

In the wet region (AEZ III), none of the soil or site properties correlated with yield (Table S2c). However, nutrient uptake was significantly influenced by several site and soil factors but only when organic matter or nutrients were added. Without fertilizer additions added to manure, improved soil chemical properties significantly increased K (P=0.01) and Ca (P=0.003) uptake, which was not observed with fertilizer additions. Convex slopes reduced N uptake (negative correlation with curvature, PC2, P=0.02) when fertilizer was applied together with manure. In contrast, by adding biochar, maize Ca uptake (P=0.03) significantly increased at lower pH (P=0.005) and higher rainfall (P=0.05).

Table 2.8. Correlation coefficients for regression of averaged maize yield on factors of 21 soil properties, environmental co-variates and terrain variables in all sites.

Treatment	Soil fertility PC1	Elevation PC2	Curvature PC3	Texture PC4	Slope gradient PC5	Aspect PC6	Soil P PC7
Control	0.05**	-0.001	0.01	0.071***	0.00004	0.001	0.01
Manure	0.07***	0.000002	0.001	0.04*	0.0014	0.001	0.022
Manure + Fertilizer	0.02	0.04**	0.003	0.04*	0.02	0.01	0.04*
Biochar + Fertilizer	0.003	0.08****	0.03*	0.0003	0.02	0.021	0.02

***, **, *, ns: significant at P<0.001, 0.01, 0.05 respectively, n=284.

Table 2.9. Correlation coefficients for regression of total plant nutrient uptake on factors of 21 soil properties, environmental co-variates and terrain variables in all sites along the environmental gradient. N=284

Treatment	Nutrient	Soil fertility PC1	Rainfall PC2	Curvature PC3	Texture PC4	Slope gradient PC5	pH PC6	Soil P PC7
Control	N	0.07 **	0.02	0.002	0.03ns	0.001	1.00E-06	-0.02
	P	0.05**	-0.0014	-0.00003	0.02*	0.01	0.01	-0.001
	K	0.06 **	-0.00003	3.00E-06	0.04**	0.004	0.01	-0.0002
	Ca	0.03 *	0.0003	-0.000004	0.05**	0.004	0.003	-0.01
	Mg	0.05 **	0.01	0.0002	0.04*	0.01	0.001	-0.01
Manure	N	0.08 ***	0.001	-0.01	0.02	-0.001	0.01	-0.004
	P	0.04 **	-0.01	-0.03*	0.01	0.001	0.04**	-0.0002
	K	0.061**	-0.003	-0.01	0.01	0.002	0.02	-0.001
	Ca	0.0033	0.0001	-0.0002	0.0002	-0.00002	0.001	-0.0004
	Mg	0.04 **	1.00E-05	-0.01	0.002	0.001	0.012***	-0.003
Manure + Fertilizer	N	0.013	0.04 **	-0.01	0.002	-0.003	-0.01	-0.021
	P	0.011	0.01	-0.03	0.001	-0.004	-0.001	-0.01
	K	0.01	0.003	-0.01	0.01	1.00E-04	0.01	-0.001
	Ca	0.01	0.001	-0.002	0.02	0.003	0.01	-0.001
	Mg	0.01	0.03*	-0.01	0.002	0.001	-0.00002	-0.01
Biochar + Fertilizer	N	0.02	0.08 ***	-0.034*	-0.003	4.00E-05	-0.024*	0.02
	P	0.001	0.001	-0.06**	0.01	0.002	-0.001	-0.002
	K	-0.0004	0.004	-0.03*	-0.01	0.01	-0.01	-0.001
	Ca	1.00E-06	0.001	-0.01	0.0001	0.003	-0.01	-0.0002
	Mg	-0.0012	0.081 ***	-0.03*	-0.02	-0.001	-0.02	-0.003

***, **, *, ns: significant at $P<0.001$, 0.01, 0.05 respectively.

4. Discussion

4.1. Nutrient release from organic amendments

Nutrient release by decomposition of organic soil amendments is central to the success of CF and important for resource-poor farmers. The greater yields with animal manure additions than the control that received compost, may be explained by the better quality of the manure, resulting in greater N application rates and N uptake especially in the drier regions. Labile organic materials (e.g., manure) are effective source of nutrients (Zingore et al., 2008) when managed correctly (Markewich et al., 2010), with reduced storage period (Tittonell et al., 2010) and enhanced soil mineral N (Delve et al., 2001; Nyamangara et al., 2003), P and K (Kihanda et al., 2006). Manure used in this study was considered to be of higher quality with 20 mg g^{-1} N and a C-to-N ratio of 18 than compost with an average C-to-N ratio of 35. Immediate benefit for crop yield increase from use of manure has been demonstrated in East and West Africa (Bationo et al., 2004; Zingore et al., 2008).

The reason for a more pronounced effect of manure additions on N uptake in the drier regions may stem from the generally greater N limitation in less weathered ecosystems (Vitousek, 1999). A greater responsiveness to N is corroborated by the maize N concentrations after additions of inorganic fertilizers. The greater N content of the gliricidia green manure and therefore greater N application (Table 1) with gliricidia additions did not result in greater crop yields than with manure in the same region, which may not be related to nutrient additions as P or K were likely not limiting plant growth.

In contrast, the stable organic additions (biochar) as compared to labile organic additions (manure) did not detectably contribute to improved N availability during the study period. Any microbial decomposition may have rather decreased availability of N by immobilization, since the C-to-N ratio of biochar was high (Table 1). However, biochar may contain some base cations such as K which become available in the short term (Lehmann et al., 2003), but direct nutrient additions with 1.5 kg K ha^{-1} (Table 1) are unlikely to have played a role for the rice biochar used in this experiment when added together with full fertilization of 100 kg K ha^{-1}.

4.2. Inorganic fertilizer additions

Productivity improvements achieved through applications of inorganic N, P and K fertilizer applied at recommended rates were over and above those of organic applications even though the nutrient application rates were comparable for gliricida and manure. The highest productivity increase with inorganic amendments was over 300% and observed in the degraded plateau, compared to the highest increase with gliricidia or manure with only 46%. Tthe amounts applied with the organic amendments were not sufficient. Low response of yields with sole OM additions may have also been caused by the need to achieve minimum thresholds for availability of nutrients limiting production in the depleted soils. This indicates that nutrient requirements were not met with the application rates of organic amendments tested in this study. This is likely the case for N, P and K with 29-35 kg ha^{-1}, 1.4-5.6 kg ha^{-1} and 22-33 kg ha^{-1}, respectively, applied with manure and gliricidia or a lower liming value with a pH of 9 of manure than the added lime in the treatments that received mineral fertilizers. Therefore, a combination of insufficient N, P and possibly low pH in high-rainfall areas may have been the reason for the low productivity found with only organic amendments, which suggest trials with increased application rates of organic amendments or at least supplementary inorganic N, P and lime applications as is observed with fertilizer additions to manure.

4.3 Soil and site effects on productivity with different soil amendments

The albeit only slightly improved crop productivity by use of organic amendments varied with type of organic amendment along the environmental gradient. Yield improvements with finer soil texture agree with typically lower SOM contents, lower water holding capacity and nutrient contents and retention in sandier soils, which was observed with and without inorganic fertilizer additions. Noteworthy is the lack of such a relationship when biochar was added instead of manure, which may possibly be explained by a greater nutrient retention either through adsorption to the biochar (Cheng et al., 2006; Liang et al., 2006) or an increase in pH and greater cation exchange capacity irrespective of soil texture. Different soil pH increases after additions of manure or biochar are unlikely as both amendments had a similar initial pH of 9.4. A greater cation retention with biochar (Lehmann, 2007) is also the most likely reason why maize Ca uptake significantly increased at lower pH and higher rainfall, i.e., under conditions where Ca is typically leached to a greater extent.

In contrast, manure additions generated greater yields when the soil texture was finer, that was not observed with biochar. Addition of nutrient-rich manure may have alleviated nutrient constraints rather than constraints of nutrient retention which would be more prevalent in sandier soils. However, SOM was likely constraining productivity across sites as indicated by the PCA.

Not all factors identified by PCA had a significant effect on crop yield. Variation in maize yield productivity and nutrient uptake may have been affected by several environmental factors such as intra-annual variations in precipitation that were not captured by our study. Our results provide evidence that full fertilization with intensifying mean annual precipitation along the gradient can explain increase in productivity, N and Mg uptake.

The soil properties that significantly increased nutrient uptake with inorganic fertilization were soil organic matter and cation availability, texture, pH and soil P in the drier region. On the other hand, texture and pH improved nutrient uptake in wetter region, where low pH and high P fixation in clayey weathered soils is typically a significant constraint to crop production. Soils in the wetter region likely have relatively high P sorption capacity and with direct P supply, organic anions released during decomposition of OM added can compete with P sorption sites and increase availability of P (Hue, 1991). Nutrient uptake on the degraded plateau was not influenced by soil properties. However, slope position had a more important influence on nutrient uptake, being greater in footslope positions. It is possible that the higher yields stem from greater water input at this slope position.

5. Conclusion

Nutrient availability but not water availability was the most important limiting factor for production in wetter regions and likely vice versa for drier regions. Biochar increased yields especially under high rainfall and low pH conditions through improved base cation availability. Ensuring adequate P additions may pose a constraint to achieving high crop yields with only organic amendments using available resources such as the tested green and animal manures or composts. Alternative organic or inorganic P sources may need to be considered. Not only nutrient delivery but also improvements of SOM were important especially in sandy soils where biochars showed the greatest potential. Long-term studies with organic amendments that either deliver nutrients or organic C across the studied environmental and soil gradients are needed to better understand the effect of C stability on soil productivity.

REFERENCES

Aagaard, P., Gibson, G., 2003a. Conservation Farming in Zambia. Conservation Farming Handbook for Hoe Farmers in Agro Ecological 1 & II Flat Culture. Lusaka Conservation Farming Unit.

Aagaard, P., Gibson, G. 2003b. Conservation Farming in Zambia. Conservation Farming Handbook for Hoe Farmers in Agro Ecological Region III, the Basics. Lusaka Conservation Farming Unit.

Andriesse, W., Giller, K.E., Jiggins, J., Löffler, H., Oosterveer, P., Woodhill, J. 2007. The Role of Agriculture in Achieving MDG1—A Review of the Leading Reports. Wageningen International, Wageningen.

Baligar, V.C. and Bennett, O.L. 1986. Nitrogen, phosphorus, potassium fertilizer efficiency a situation analysis for the tropics. Fertilizer Research 10, 147-164.

Bationo A., Vlek, P.L.G. 1997. The role of nitrogen fertilizers applied to food crop in the Sudano-Sahelian zone of West Africa. In Renard G et al. (Ed) Soil fertility management in West African land use systems. Proceedings of regional work-shop University of Hohenheim, ICRISAT Sahelian Centre and INRAN 4–8 March 1997, Niamey, Niger. Margraf Verlag, Germany.

Bationo, A., Nandwa, S.M., Kimetu, J.M., Kinyangi, J.M., Bado, B.V., Lompo, F., Kimani S., Kihanda, F., Koala, S. 2004. Sustainable intensification of crop-livestock systems through manure management in eastern and western Africa: lessons learned and emerging research opportunities. In Williams, T.O., Tarawali, S.A., Hiernaux, P., Ferna´ndez-Rivera, S. Eds. Sustainable crop-livestock production for improved livelihoods and natural resource management in West Africa. International Livestock Research Institute and Technical Centre for Agricultural and Rural Cooperation proceedings, Ibadan, Nigeria, pp 173–198.

Bationo A., Kihara J., Vanlauwe B., Waswa B., Kimetu J. 2007. Soil organic carbon dynamics, functions and management in West African agro-ecosystems. Agricultural Systems 94, 13–25.

Cheng, C.H., Lehmann, J., Thies, J.E., Burton, S.D., Engelhard, M.H. 2006. Oxidation of black carbon by biotic and abiotic processes. Organic Geochemistry 37, 1477-1488.

Cheng, Y., Cai, Z., Chang, S.X., Wang, J., Zhang, J. 2012. Wheat straw and its biochar have contrasting effects on inorganic N retention and N20 production in a cultivated Black Chernozem. Biology and Fertility of Soils 48, published online.

Chivenge, P., Vanlauwe, B., Six, J. 2011. Does the combined application of organic and mineral nutrient sources influence maize productivity? A meta-analysis. Plant and Soil 342, 1–30.

Chiwele, D., McKenzie, J. 1996. “Zambia Agricultural Sector Performance Analysis.” University of Zambia, Institute for African Studies.

Cobo, J.G., Dercon, G., Cadisch, G. 2010. Nutrient balances in African land use systems across different spatial scales, a review of approaches, challenges and progress. Agriculture, Ecosystems and Environment 136, 1–15.

Delve, R.J., Cadisch, G., Tanner, J.C., Thorpe, W., Thorne, P.J., Giller, K.E. 2001. Implications of livestock feeding management on soil fertility in the smallholder farming systems of sub-Saharan Africa. Agriculture, Ecosystems and Environment 84, 227–243.

Gerrard, A.J. 1981. Soils and landforms, an integration of geomorphology and pedology. George Allen and Unwin Ltd., London.

Goyal, S., Chander, K., Mundra, M.C., Kapoor, K.K. 1999. Influence of inorganic fertilizers and organic amendments on soil organic matter and soil microbial properties under tropical conditions. Biology and Fertility of Soils 29, 196–200.

Haefele, S.M., Konboon, Y., Wongboon, W., Amarante, S., Maarifat, A.A., Pfeiffer, E.M., Knoblauch, C. 2011. Effects and fate of biochar from rice residues in rice-based
systems. Field Crops Research 121, 430–440.

Hue, N. V. 1991. Effects of organic acids/anions on P-sorption and phytoavailability in soils with different mineralogies. Soil Science 152, 463–471.

Kang, B.T. 1993. Alley cropping past achievements and future directs. Agroforestry Systems 23, 141–155.

Kihanda, M., Warren, G.P., Micheni, A.N. 2006. Effect of manure application on crop yield and soil chemical properties in a long-term field trial of semi-arid Kenya. Nutrient Cycling in Agroecosystems 76, 341–354.

Kimetu J.M., Mugendi D.N., Palm C.A, Mutuo P.K., Gachengo C.N., Bationo A., Nandwa S., Kungu J.B. 2004. Nitrogen fertilizer equivalencies or organics of differing quality and optimum combination with inorganic nitrogen source in Central Kenya. Nutrient Cycling in Agroecosystems 68, 127–135.

Larson, B. A., Frisvold, G. B. 1996. Fertilizers to support agricultural development In sub-Saharan Africa, what is needed and why. Food Policy 21, 509–525.

Lehmann, J., Cravo, M.S., deMacêdo. J.L.V., Moreira, A., Schroth, G. 2001. Phosphorus management for perennial crops in central Amazonian upland soils. Plant and Soil 237, 309-319.

Lehmann J., da Silva Jr. J.P., Steiner C., Nehls T., Zech W., Glaser B. 2003. Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin- fertilizer, manure and Biochar amendments. Plant and Soil 249, 343- 357.

Lehmann, J., Gaunt, J., Rondon M. 2006. Bio-char sequestration in terrestrial Ecosystems – a review, Mitigation and Adaptation Strategies for Global Change 11, 403–427.

Lehmann, J. 2007. Bio-energy in the black. Frontiers in Ecology and the Environment 5, 381-387.

Lewis, D., Bell, S., Fay, J., Bothi, K.L., Gatere, L., Kabila, M., Mukamba, M., Matokwani, E., Mushimbalume, M., Moraru, C., Lehmann, J., Lassoie, J., Wolfe, D., Lee, D., Buck, L., Travis, A. 2011. Community Markets for Conservation (COMACO) links biodiversity conservation with sustainable improvements in livelihoods and food production. PNAS 108, 13957 –13962.

Liang, B., Lehmann, J., Solomon, D., Kinyangi, J., Grossman J, O'Neill B, Skjemstad, J.O., Thies, J., Luizão, F.J., Petersen, J., Neves, E.G. 2006. Black carbon increases cation exchange capacity in soils. Soil Science Society of America Journal 70, 1719–1730.

Mafongoya, P.L., Giller, K.E., Palm, C.A. 1998. Decomposition and nitrogen release patterns of tree prunings and litter. Agroforestry Systems 38, 77-79.

Mafongoya, P., Bationo, A., Kihara, J., Waswa, B. 2006. Appropriate technologies to replenish soil fertility in southern Africa. Nutrient Cycling in Agroecosystems 76, 137–151.

Markewich, H.A., Pell, A.N., Mbugua, D.M., Cherney, D.J.R., Van, H.M., Lehmann, J., Robertson, J.B. 2010. Effects of storage methods on chemical composition of manure and manure decomposition in soil in small-scale Kenyan systems. Agriculture, Ecosystems and Environment 139, 134–141.

Moore, I.D., Gessler, P.E., Nielsen, G.A., Peterson, G.A. 1993. Soil attributes prediction using terrain analysis. Soil Science Society of America Journal 57, 443–452.

Moraghan, J.T., Mascagni, H.J. 1991. Environmental and soil factors affecting micronutrient deficiencies and toxicities. In J.J. Mortvedt. Ed. Micronutrients in agriculture. 2nd ed. SSSA Book Ser. 4. SSSA, Madison, WI. pp. 371– 425.

Mtambanengwe, F., Mapfumo, P., Vanlauwe, B., 2006. Comparative short-term effects of different quality organic resources on maize productivity under two different environments in Zimbabwe. Nutrient Cycling in Agroecosystems 76, 271-284.

Mugendi, D.N., Nair, P.K.R., Mugwe, J.N., O'Neil, M.K., Woomer, P.L. 1999. Alley cropping of maize with calliandra and leuceana in the subhumid highlands of Kenya. Part 1. Soil fertility changes and maize yield. Agroforestry Systems 46, 39–50.

Mugwira, L.M., Murwira, H.K., 1997. Use of Cattle Manure to Improve Soil Fertility in Zimbabwe: Past and Current Research and Future Research Needs Soil Fertility Network Research Results Working Paper No. 2.

Murwira H.K., Mutuo P., Nhamo N., Marandu A.E., Rabeson R., Mwale M., Palm C.A. 2002. Fertilizer equivalent values of organic materials of differing quality. In

Pennock, D.J., and E. de Jong. 1987. The influence of slope curvature on soil erosion and deposition in hummock terrain. Soil Science 144, 209–217.

Nyamangara, J., Piha, M.I., Giller, K.E. 2003a. Effects of combined cattle manure and mineral nitrogen on maize N uptake and grain yield. African Crop Science Journal 11, 289–300.

Nyamangara, J., Bergstrom, L.F., Piha, M.I., Giller, K.E. 2003b. Fertilizer use efficiency and nitrate leaching in a tropical sandy soil. Journal of Environmental Quality 32, 599–606.

Nziguheba, G., Palm, C.A., Buresh, R.J., Smithson, P.C. 1998. Soil phosphorus fractions and adsorption as affected by organic and inorganic sources. Plant and Soil 198, 159–168.

Nziguheba, G., Merckx, R., Palm. C.A. 2002.Soil phosphorus dynamics and maize response to different rates of phosphorus fertilizer applied to an Acrisol in western Kenya. Plant and Soil 243, 1-10.

Oliva, S.R., Raitio, H., Mingorance, M.D. 2003. Comparison of two wet digestion procedures for multi-element analysis of plant samples. Communications in Soil Science and Plant Analysis 34, 2913–23.

Palm, C.A., Myers, R.J.K., Nandwa, S.M. 1997. Combined use of organic and inorganic nutrient sources for soil fertility maintenance and replenishment. In Buresh

RJ, Sanchez PA, Calhoun F. Eds. Replenishing soil fertility in Africa SSSA Special publication No 51. American Society of Agronomy, Madison, pp 193 –217.

Palm, C.A., Giller, K.E., Mafongoya, P.L., Swift, M.J. 2001. Management of organic matter in the tropics: translating theory into practice. Nutrient Cycling in Agroecosystems 61, 63–75.

Sanchez, P.A. 2002. Soil fertility and hunger in Africa. Science 295, 2019–2020.

Sanchez, P.A., Palm, C.A., Szott, L.T., Curvas, E., Lal, R. 1989. Organic input management in tropical agroecosystems. In Dynamics of soil organic matter in tropical ecosystems. D.C. Coleman, D.C., Oades, M.J., Uehara, G. Eds. pp.125-152.

Schenkel, Y., Bertaux, P., Vanwijnbserghe, S., Carre J. 1998. An evaluation of the mound kiln carbonization technique. Biomass and Bioenergy 14, 505-516.

Schmidt, M.W.I., Noack A.G. 2000. Black carbon in soils and sediments, Analysis, distribution, implications, and current challenges. Global Biogeochemical Cycles 14, 777-794.

Schroth, G., Oliver, R., Balle, P., Gnahoua, G.M., Kanchanakanti, N., Leduc, B., Mallet, B., Peltier, B., Zech, W. 1995. Alley cropping with *Gliricidia sepium* on high base status soil following forest clearing: effects on soil conditions, plant nutrition and crop yields. Agroforestry Systems 32, 261–276.

Smaling E.M.A., Nandwa, S., Janssen, B.H. 1997. Soil fertility in Africa is at stake. In Buresh, R.J., Sanchez, P.A., Calhoun, F. Eds. Replenishing soil fertility in Africa. Soil Science Society of America (SSSA), SSSA Special Publication 51, Madison, pp 47-61.

Solomon, D., Lehmann, J., Kinyangi, J., Amelung, W., Lobe, I., Pell, A., Riha, S., Ngoze, S., Verchot, L., Mbugua, D., Skjemstad, J., Schafer, T. 2007. Long-term impacts of anthropogenic perturbations on dynamics and speciation of organic carbon in tropical forest and subtropical grassland ecosystems. Global Change Biology 13, 511–530.

Tittonell, P., Vanlauwe, B., Corbeels, M. 2008. Yield gaps, nutrient use efficiencies and response to fertilisers by maize across heterogeneous smallholder farms of western Kenya. Plant and Soil 313, 19–37.

Tittonell, P., Rufino M.C. Janssen B.H., Giller, K.E. 2010. Carbon and nutrient losses during manure storage under traditional and improved practices in smallholder crop-livestock systems-evidence from Kenya. Plant and Soil 328, 253-269.

Vanlauwe, B., Kihara, J., Chivenge, P., Pypers, P., Coe, R., Six, J. 2010. Agronomic use efficiency of N fertilizer in maize based systems in sub-Saharan Africa within the context of integrated soil fertility management. Plant and Soil 339, 35-50.

Vitousek, P.M., Sanford, R.L. 1986. Nutrient cycling in moist tropical forest. Annual Reviews Ecology, Evolution and Systematics 17, 137–167.

Vitousek, P.M. 1999. Nutrient limitation to nitrogen fixation in young volcanic sites. Ecosystems 2, 505-510.

Vitousek, P.M., Porder, S., Houlton, Z.B., Chadwick, O.A. 2010. Terrestrial phosphorus limitation mechanisms, implications, and nitrogen–phosphorus interactions. Ecological Applications 20, 5–15.

Wallace, J.S. 1996. Water balance of mixed tree-crop systems In Ong, C.K., Huxley, P. Eds Tree–crop interactions, a physiological approach. AB International, Wallingford, UK. pp. 189–234.

Zingore, S., Delve, R., Nyamangara, J., Giller, K. 2008. Multiple benefits of manure, the key to maintenance of soil fertility and restoration of depleted sandy soils on African smallholder farms. Nutrient Cycling in Agroecosystems 80, 267–282.

CHAPTER 3

SPATIAL DISTRIBUTION OF SOIL ORGANIC CARBON AND NITROGEN DYNAMICS UNDER CONSERVATION FARMING IN ZAMBIA

Abstract

A study was conducted to examine spatial changes in soil organic matter (SOM) quantity and quality after adoption of conservation farming (CF) in Zambia over a period of 10 years, as a result of different resource allocation of crop residues and compost dynamics over time under a 10-year chronosequence of conservation farming (CF). Total soil organic C (SOC) and N contents were initially 8% and 12% greater in planting basins than between crops (rows; n=6). The difference of both SOC and N between basins (R^2=0.31) and rows (R^2=0.16) decreased with increasing years under CF suggesting that build-up of OM was greater in basins than in rows. Carbon and N in the labile SOM pool (free-light fraction) in basins increased to a greater extent in basins than rows. Mineralization of C per unit SOC in basins (R^2=0.83) increased with years under CF indicating an accumulation of more labile SOC, whereas the amount of SOC mineralized in rows did not change with longer implementation of CF. In contrast, potential mineralized N (PMN) increased in both basins (R^2=0.60) and rows (R^2=0.79) with years of CF implementation, albeit in basins more rapidly than in rows. Carbon and mineralizable N accrued to a greater extent in planting basins that received organic amendments despite digging of planting stations, but stability of SOC was greater in areas of the CF fields that received only crop residues.

1. Introduction

Soil fertility depletion in smallholder agricultural systems in sub-Saharan Africa (SSA) presents a formidable challenge both for food production and environmental stability. SSA must overcome soil fertility depletion which has resulted from decades of nutrient mining by small-scale farmers that threatens the region's food security. The main cause of land degradation in SSA is failure by smallholder farmers to intensify agricultural production in a manner that maintains soil productivity (Mateete et al., 2010). Further, poor targeting of soil management interventions is also a critical constraint to managing soils. Conservation agriculture (CA) commonly regarded as appropriate for a wide range of smallholder conditions (FAO, 2008), particularly seeks to address the complexity of soil degradation by agricultural practices that deplete soil organic matter (SOM) and nutrient contents of soil. Adoption of CA in Africa, especially on smallholder farms, has been slow. Considerable areas under CA are only found in Ghana (Ekboir et al., 2002), Zambia (Haggblade and Tembo, 2003; Mazvimavi and Twomlow, 2009), South Africa (Giller et al., 2009), Tanzania (Shetto and Owenya, 2007), and Zimbabwe (Mazvimavi and Twomlow, 2009; Marongwe et al., 2011).

Implementation of soil conservation management systems in Zambia began in the 1990s to reduce widespread soil degradation and to improve SOM which is important for securing soil fertility (Zech et al., 1997) and consequently food security. A form of CA in Zambia, which is known under the term conservation farming (CF), includes dry season land preparation and minimum tillage; repeated use of small planting holes (basins) for planting and for soil amendments; no burning of crops residues but rather residue retention as mulch to suppress weed growth, to return nutrients to the soil, and to help retain moisture; early and continuous weeding; and rotating and/or interplanting with 30% nitrogen-fixing crops (Lewis et al., 2011; CFU, 2003).

Reduced tillage and residue retention are both CF practices (CFU, 2003) that may augment soil organic carbon (SOC) stabilization in sub-humid tropical soils (Six et al., 2002). Removal of crop residues from fields is recognized to increase SOC decline especially when coupled with conventional tillage (Yang and Wander, 1999; Mann et al., 2002). Conversely, addition of stover results in greater increases in SOC than if stover is removed (Mann et al., 2002) ensuring important improvements in soil quality and soil fertility (Six et al., 2000). Even after 15 years of no-till, SOC decreased by 75% with maize residue removal on a Nigerian Alfisol following forest clearing while residue retention resulted in twice as much SOC than residue removal (Juo et al., 1996). Tillage induces rapid mineralization and loss of SOC and nitrogen (N) from the soil, and plays a significant role in the manipulation of nutrient storage and release from soil organic matter (SOM). Type and length of tillage practice influence the amount of SOM, the rate of SOM turnover and its distribution among size fractions down the profile (Cambardella and Elliot, 1994; Six et al., 2002a, b). Minimum tillage results in accumulation of SOC and N within aggregates (Six et al., 2000, 2001; De Gryze et al., 2004), in greater aggregation and higher standing stocks of SOM compared with conventional practices (Carter et al., 1998). Therefore, SOC accrual is expected as an important benefit of CF, but the spatial distribution of SOC between inter-row positions and planting basin as implemented in CF in Zambia is not known.

Although total SOC and N are important for long-term assessments of sustainable land management systems (Follett et al., 1987; Sá et al., 2009), particulate organic C and N (Moran et al., 2005), SOC within aggregates (Six et al., 2000; Sohi et al., 2001) and biologically active SOC and N have been shown to be equally and sometimes more responsive to changes in soil management than total contents (Barrios et al., 1996), which makes them excellent indicators of soil quality (Gregorich, et al., 1994). The dynamics of SOC with change in land use and management can better be explained by the way SOC is allocated in different fractions of SOM (Lehmann et al., 1999; Tan et al., 2007). These fractions exhibit different rates of biochemical and microbial degradation (Stevenson, 1994) as well as different accessibility and interactions (Sollins et al., 1996). Numerous studies (Cambardella and Elliott, 1992; Franzluebbers and Arshad, 1997; Franzluebbers and Stuedemann, 2002) have suggested that certain SOC fractions are likely to respond to land use change more rapidly than total SOC and may therefore serve to assess the changes between basins and rows that receive different amounts and forms of organic matter in CF.

Changes in SOM by changes in organic matter additions, retention of crop residues and changes in mineralization through reduced soil tillage or digging of basins may operate at different time scales. The accumulation of low quality organic residues at the soil surface may initially lead to N immobilization followed by greater N mineralization (Palm et al., 2001; Gentile et al., 2008). On the other hand, some practices in CF may have immediate benefits, such as direct additions of manure that can replenish high losses of SOM in the short term (Glaser et al., 2001), the early planting and the better moisture capture through digging basins as planting stations. Tillage is known to reduce SOC and increase soil N mineralization on the short term but information on the spatial distribution of SOC and N quantity and quality in CF that increases net soil N mineralization and simultaneously maintains a considerable amount of SOC is poorly known.

Recognizing the different spatial allocation of organic amendments and crop residues in CF, the objective of this study was to assess the changes of SOC and nitrogen in planting basins and between crops over a 10-year establishment period in the hot sub-humid tropics in Zambia. We hypothesized that installations of the planting basins in CF would initially reduce SOC compared to other areas of the field, addition of compost to basins increase SOC and increase potential mineralizable N, whereas crop residue return would decrease potential mineralizable N in rows.

2. Materials and methods

2.1. Site description

The experimental sites are located in Agroecological Zone (AEZ) II. AEZ zones are classified based on average annual rainfall and length of growing season (Chiwele and McKenzie, 1996). AEZ II is further subdivided into IIa and IIb based on differences in soil properties. This study was restricted to AEZ IIa. Soils in this zone are classified as Haplic Lixisol, and characterized by a clay-enriched lower horizon, fine loamy texture with 4-42% clay, with low CEC between 7 and 159 mmolc kg^{-1}, and high saturation of bases of 97 to 99%, pH values of 4.6 to 6.8, low organic C contents of 2.8 to 26.9 g kg^{-1} and N contents of 0.3 to 1.9 g kg^{-1}. Climate is influenced by the Inter-Tropical Convergence Zone (ITCZ) with mean annual rainfall of 1000 mm and mean monthly precipitation varying significantly from zero to 170 mm. Rainfall pattern is unimodal with rains falling between November and April, followed by a dry season from May to October (Munyati, 2000). Elevation averages about 1000 m above sea level (a.s.l.) while temperature ranges between 19°C and 36°C. The topography of the region is characterized by gently undulating terrain. Topography plays a minor role in the determination of vegetation patterns and there is no obvious toposequence (Cauldwell et al., 2000). The landscape is mostly covered with mosaic forest shrubland and grassland. Chidumayo (1987) characterized the phytoregion as central dry miombo region. Miombo woodland dominates the vegetation, and small areas of grassland (dambo) and shrubland which include termitaria thickets and dry deciduous thickets.

2.2. Chronosequence field selection

Mumbwa district was specially chosen as a representative of the oldest hand-hoe CF region in Zambia. Farmers in this district are small scale holders who have been under the Conservation Farming Unit (CFU) starting from 1996 (CFU, 2012). Since CFU's inception, the majority of the farmers have progressed from CF hand-hoe farming to utilizing animal draft power (ADP). However, many farmers still maintain a minimum of a *Lima* (quarter of a hectare) of the land in hand-hoe cultivation.

For this study farms were chosen that practiced hand-hoe CF for different periods of time. The identification of when fields were converted from traditional farming (TF) to CF was done in consultation with the CFU office in Mumbwa. The targeted farmers comprised of those practicing hand-hoe farming in CF farming.

The effects of SOM accrual over conversion time under CF were therefore studied using a chronosequence (false-time series) approach (Kimetu et al., 2008). A chronosequence approach defines the time that has elapsed since a farmer converted from TF to CF, which has been frequently used to study land use conversion (Neill et al., 1995; Lobe et al., 2001; Zingore et al., 2005; Solomon et al., 2007; Kimetu et al.,

2008) if long-term field experiments do not exist. Fields with different lengths of continuous practice of CF were identified on the same soil type, under the same climatic conditions and with all maize planted as the previous crop. The chronosequence stretched from recent conversions (1 year) to 10 years and ages were grouped into 2-year intervals giving conversion points of 0, 2, 4, 6, 8 and 10 years. For each conversion age class, ten replicate sites were included in the study giving a total of 60 study sites using a completely randomized design for age, with a nested design for soil management (basins versus rows). Some identified farms had several fields of different conversion ages in existence. Care was taken to ensure that CF was practiced continuously for the time period since conversion without changes in practice. In-depth interviews were conducted with farmers to establish conversion ages and practices before fields were included in this study.

2.3. Field sample collection and laboratory analyses

Soil samples were collected in June 2007 from the top 0.15 m using an auger of 0.05 m diameter. For CF plots, soil was collected from two positions, the planting holes (basins) and between the planting holes (rows). A composite sample was made from six samples collected randomly from different locations of each position. Soil was air-dried and passed through a 2-mm sieve. Texture was assessed using a simple and rapid quantitative method developed by Kettler et al. (2001) in which particles are dispersed using 3% hexametaphosphate ($NaPO_3$) and sedimentation steps are used.

Total SOC and N were determined by dry combustion after fine-grinding soil sub samples with a ball mill (Retsch® MM301, Retsch Inc, Newton PA, USA). Samples were analyzed for total C and N contents with a Europa ANCA-GSL CN auto-analyzer (PDZ Europa Ltd., Sandbach, UK). Soils had no free Ca carbonates, since pH values were below 7 and total C therefore represents SOC. Soil particle- size was determined by simplified rapid method using sodium hexametaphosphate developed by Kettler et al. (2001).

2.4. Incubation experiment

An incubation trial was conducted to evaluate the SOC stability and N mineralization potential. Constant temperature laboratory incubations at 30 C (Sanchez et al., 2001) were set up to monitor CO_2 evolution of 20 g of air-dried soil. Briefly, soil moisture content was adjusted to field capacity (determined gravimetrically to be 30% – 40% w/w depending on the site) after which the soil was incubated in 1-L mason jars for one week. Moisture content was maintained throughout the incubation period by repeated weighing. CO_2 released from soil was trapped using 20-mL of 0.5 M KOH put in 30-mL Qorpak vials. The amount of CO_2 absorbed by the KOH solution was estimated by measuring the change in electrical conductivity in the KOH trap at time zero and after seven days and compared to a standard curve (Strotmann et al., 2004). KOH was chosen for its sensitivity in absorbing CO_2 (Taok et al., 2007). The rate of respiration was calculated by dividing the CO_2 respired by the time of incubation.
Potentially mineralizable N (NO_3^--N) was measured by incubating 10 g of soil under anaerobic conditions at 30°C for 7 days as described by Drinkwater et al., 1996.
NO_3^--N was measured in 2 M KCl extracts at the beginning and the end of incubation period (Bremner, 1965). Data are presented on an oven dry weight basis.

2.5. Organic matter fractionation

To study the changes of different SOC pools over time, we applied a combined density and physical disruption energy to separate three fractions of organic matter (Sohi et al., 2001). Each sample of 15.0 g air dried soil was added to 0.09 L of NaI solution, prepared to a density of 1.8 g cm^{-3} (determined by hydrometer). Six 0.25-L polycarbonate centrifuge bottles were swirled by hand for 30 sec to allow particles of SOM released from the breakdown of unstable aggregates to float off. The downward sedimentation of heavy particles was accelerated by centrifuging the bottles at 8000 × *g* for 30 min. Floating free light fraction was recovered from each bottle, together with the NaI solution, using a trimmed 25-mL plastic pipette (Sohi et al., 2001). This set-up was attached to a vacuum flask and a water aspirator suction line via 6-mm diameter tubing in order to aspirate the supernatant containing the free light fraction. The free light fraction was then isolated by decanting the contents of the vacuum flask over a glass fiber filter (type GF/A, 47 mm diameter, 1.6 μm retention; Whatman) in a vacuum filtration unit (Millipore). The retained material on the filter paper was rinsed thoroughly with deionised water using a wash bottle and a separate collector in order to remove soil mineral and salt contaminants. The receiver apparatus filter platform and threads of the filtration unit were rinsed in de-ionized water and dried before re-assembling the alternate collector for the next sample extraction.

In a second step, we isolated the intra-aggregate light fraction by re-suspending the contents of the centrifuge bottles and sonicating (Misonix XL 2020, Farmingdale, NY) for 200 sec. Soil suspensions in centrifuge bottles were dispersed by adjusting the probe horn (9.5 mm diameter) submersion to 19 mm depth. Actual calorimetric energy transfer was 0.25 kW, measured by temperature change in 100 mL cold water over 5 min (Sohi et al., 2001), then verified after 5 sample runs. Sonication resulted in energy inputs of 1.50 kJ g^{-1} soil. Because of the heat generated, the centrifuge bottles were cooled in 1.0-L ice-packed beakers. After centrifugation, the intra-aggregate light fraction was recovered using the same procedure as described for the free light fraction. In the last step, the residual organomineral fraction was recovered following 3 runs of centrifugation (8000× *g*, 15 min.) with deionised water to remove the excess NaI salt.

Total soil C and N were determined by dry combustion after fine grinding soil using a Mixer Mill (MM301, Retsch, Germany). Samples were analyzed for C and N contents with a Europa ANCA-GSL CN analyzer (PDZ Europa Ltd., Sandbach, UK). The C and N content per unit soil was calculated after multiplying the C or N concentration (mg g^{-1}) of the fraction with the dry weight yield of that fraction per kg soil. Based on the fraction chemical and physical attributes (Sohi et al., 2001), the free light fraction denotes a labile SOC pool, the intra-aggregate fraction a stable aggregate-protected pool, and the organomineral fraction a stable SOC pool.

2.5. Statistical analyses

Levels of C and N in soil collected from both hand-hoe CF and TF with increasing duration of CF were compared in a completely randomized design with soil management nested within age since conversion from TF to CF using regression analysis followed by analysis of variance (ANOVA in JMP; SAS Institute Inc., Cary, NC). Mean separation was computed with significant difference set at $P < 0.05$.

3. Results

3.1. Total soil C and N

Under CF, total soil C and N increased gradually over the first 6 years and continually decreased thereafter in basins and in rows (Fig. 1a and 1b). Similarly, clay contents decreased in older conversions (Supplementary Online Fig. S1), largely explaining the temporal trends (Supplementary Online Fig. S2). Total SOC was slightly higher in basins (5.2 g kg^{-1} to 21.1 g kg^{-1}) than in rows (4.2 g kg^{-1} to 20.7 g kg^{-1}). Similarly, soil N was on average greater in basins (0.4 g kg^{-1} to 1.7 g kg^{-1}) than rows (0.3 g kg^{-1} to 1.8 g kg^{-1}). The difference of total SOC and N between basins and rows decreased with increasing years under CF (Fig. 1c and 1d).

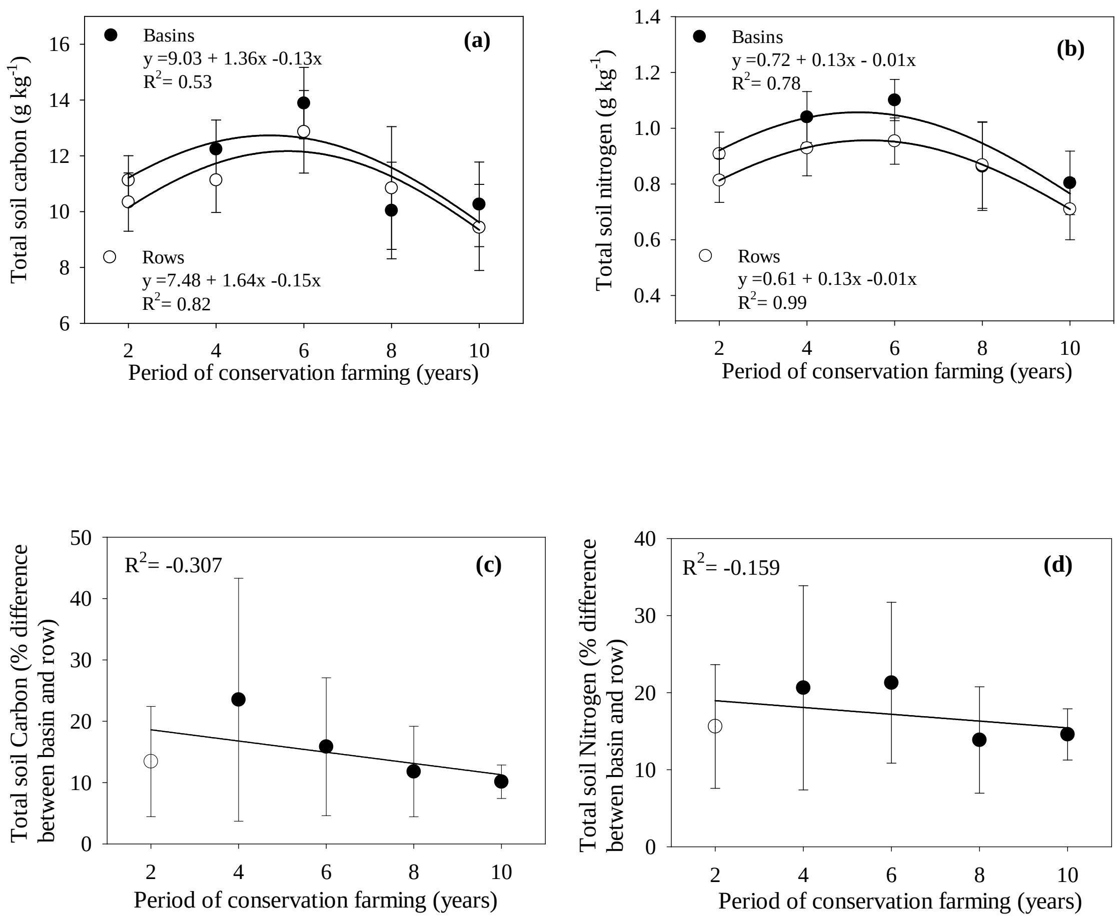

Figure 3.1. Comparison of total C and N at different locations in soils under CF in a 10-year chronosequence. Amount of total soil C (mg g-1) (a) and total soil N (b) from basins were compared to total soil C and N in rows. Percent difference of total soil C (c) and N (d) between basins and in rows under CF. Vertical bars indicate standard error. Significance is set at P<0.05, n=10.

3.2. Soil C-CO_2 evolution and potential N mineralization

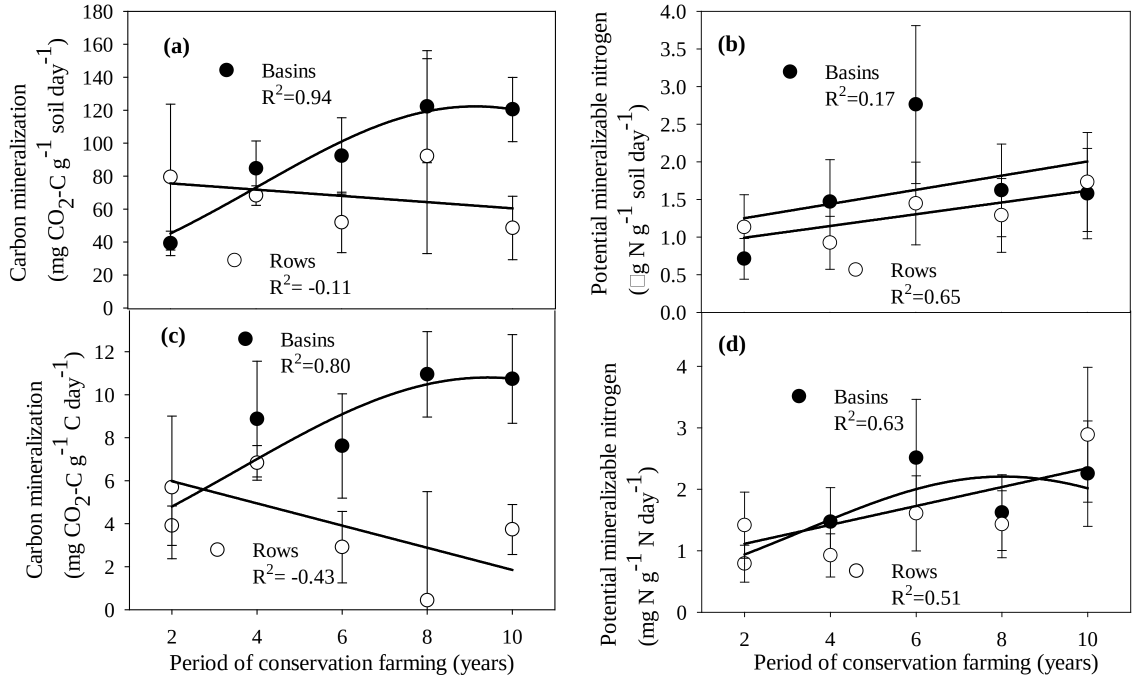

Figure 3.2. Carbon (a) and N (b) mineralization in soil and C (c) and N (d) mineralization per unit C and N, respectively, during laboratory incubation of CF soils from basins and in rows in Zambia (means and standard errors, n=6).

Carbon mineralization per unit SOC during the 7 day-incubation varied from 3.91 to 10.95 µg CO_2-C g^{-1} C per day in basins and 0.43 to 6.83 µg CO_2-C g^{-1} C per day in rows, with similar trends per unit soil (Fig. 3-2). Carbon mineralization in basins increased (R^2=0.83) with years under CF whereas the amount of SOC mineralized in rows did not change (R^2=0.00) with longer implementation of CF (Fig. 3-2a and c).

Potential mineralized N (PMN) per unit soil over 7 days of incubation varied from 1.89 to 6.11 µg N g^{-1} soil day^{-1} in basins and 2.46 to 4.61 µg N g^{-1} soil day^{-1} in rows. In contrast to the C mineralization, PMN initially increased equally in basins and in rows (Fig. 3-2ba and d).

3.3. Soil organic matter: C and N fractions

Lower decreases in SOC captured in the stable organomineral fraction (OMF) were observed in basins and significant losses in rows (R^2= 0.92; P=0.01) (Fig. 3c). The difference in FLF between basins and rows increased gradually over time, basin having greater contents than rows. There was no difference in intra-aggregate fractions (IAF) between basins and rows (Fig. 3b).

Similar observations were made for N. Stable OMF and FLF N was lower in rows than basins and that difference increased over time (Fig. 4a and c). OMF N in rows showed a significant decline (R^2 =0.95; P=0.05) with duration of farming. Nitrogen in IAF was not different in basins and rows (Fig. 4b).

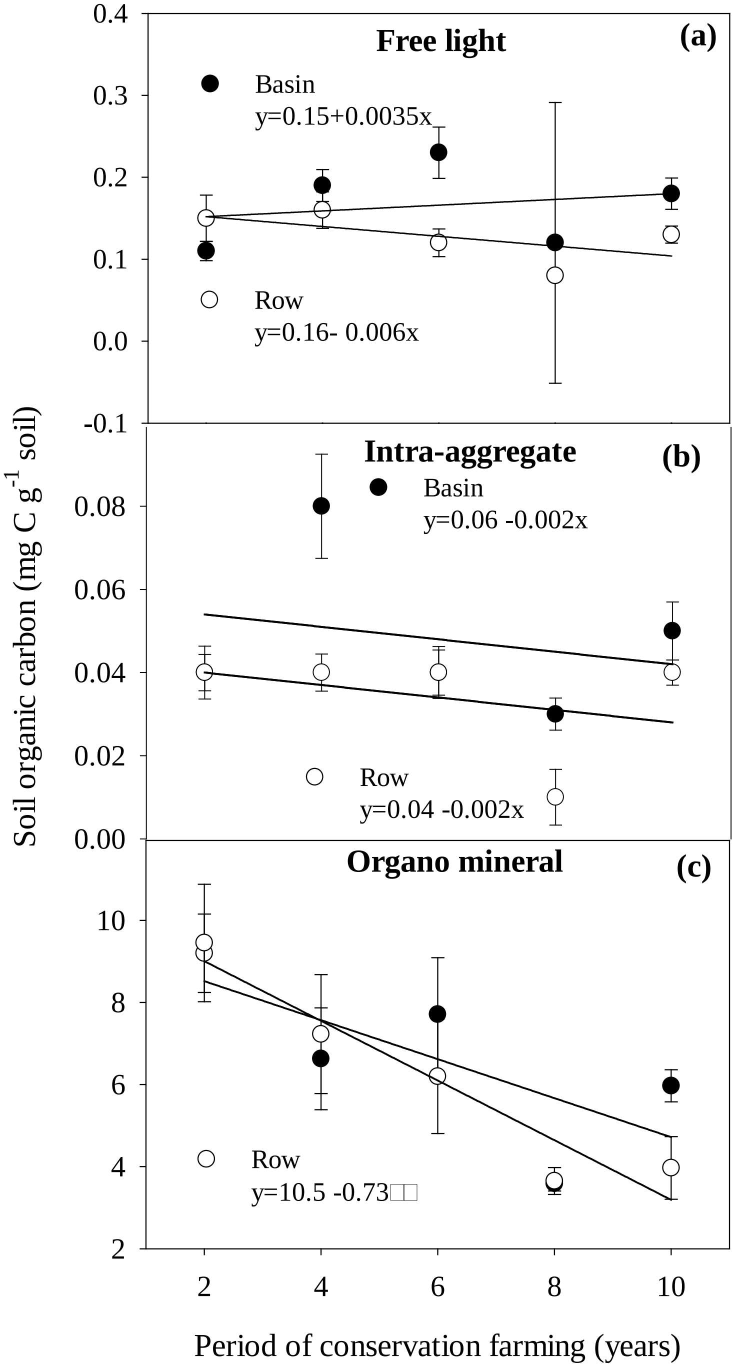

Figure 3.3. Differences in SOC in CF basins and rows (a) (labile [free-light], (b) stable intra-aggregate and, (c) stable organomineral fractions.

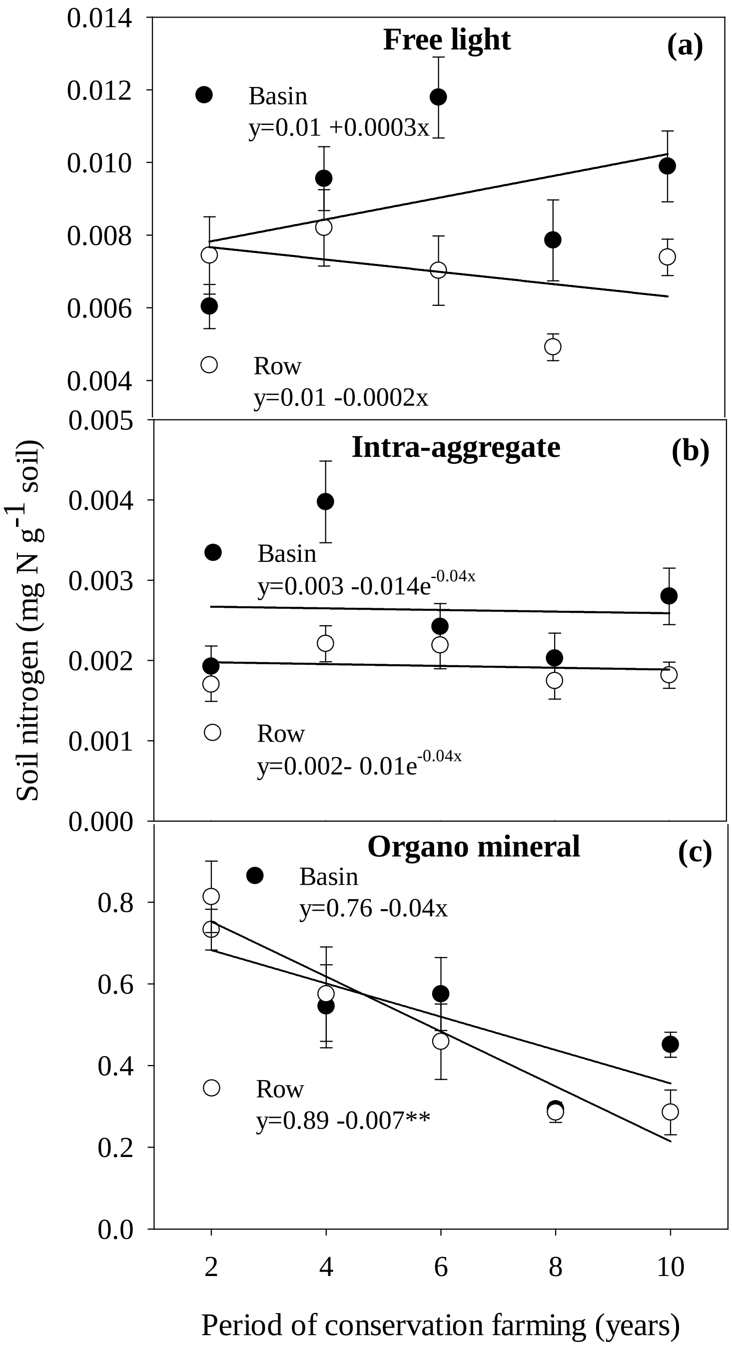

Figure 3.4. Differences in total N in CF basins and rows (a) (labile (free-light), (b) stable intra-aggregate and, (c) stable organomineral fractions. Vertical bars represent standard error, n=4.

4. Discussions

4.1. Spatial variations of SOC and N contents in CF

The difference of total SOC and N between basins and in rows (Fig. 1c & d) decreased with increasing years indicating that build-up of organic matter in basins was greater compared to the location in rows. In contrast, Dalal et al. (1991) and Sa et al. (2001) observed long term SOC increases in the surface soil layer because of interactive effects of zero tillage and retention of residues. Soils which have undergone disturbance have lower SOC concentration than undisturbed soils and those with surface mulch (Jarecki and Lal, 2003; Lal et al., 2007). SOC in basins increased proportionally to a greater extent because the organic matter additions in the basins must have initially compensated for the digging of the holes and exposure of subsoil. The crop residue return was initially less effective than the soil amendments additions in improving SOC in this study.

However, the trends differed over time. The decline in difference between the two locations may result from the annual digging of the basins only, whereas the soil between the plants remained undisturbed. In addition, recommended early land preparation starting in May (Haggblade and Tembo, 2003), leaves the soil exposed to high temperatures until mid-November that accelerates C loss through decomposition (Bationo et al., 2006). The annual additions of organic soil amendments into the basins are expected to concentrate C in the basins. However there is insufficient evidence to conclude that the amount of OM added is sufficient to compensate for the re-digging of the basins on the long term.

In comparison, zero-tillage as practiced in rows coupled with higher organic matter input through crop residue retention moderates soil temperature (Paustian et al., 1997; Hobbs, 2007), and may consequently reduce C mineralization (Stockfisch et al., 1999) and maintains SOC at equal levels to those observed in short-term zero-tillage (Six et al., 2000; Pandey et al., 2010). Lack of a steady increase in SOC in rows in comparison to basins over time as observed in this study possibly resulted from a critically low supply of residues as a consequence of several competing uses for crop residues, high decomposition rates of exposed crop residues and termite attacks. Further, competition for crop residues by communal livestock grazing after harvest may have reduced the amount of residues retained as soil cover.

4.2. SOC and N quality

The decreasing SOC stability indicated by greater CO_2 evolution in basins in contrast to rows may stem from the additions of more labile composts or manures into these basins than the crop residues which may be more stable (Gentile et al., 2011). Moreover, tillage by digging the basins improves soil mixing and aeration which may break up aggregates that typically confer stability to SOC. This is corroborated by a greater proportion of labile SOC pool (free-light fraction) observed in basins than in rows. Lower SOC stability in basins than rows may also be a result of a greater quantity of organic amendments added per unit area in the basins than the crop residue retained in the rows per unit area.

Potential mineralizable N (PMN) did not differ between basins and rows over time (Fig. 3b & d), suggesting that even residue return is able to improve N availability in CF. Barrios et al. (1996b) reports similar results of highest PMN for continuous maize with residues added each season. This is because residue addition increases aggregation (Gentile et al., 2010) and N is occluded in microaggegates within macroaggregates (Gulde et al., 2008). Others report PMN increases by reducing tillage. The similar dynamics of PMN in rows compared to basins is curious in the light of a lack of lower C stability as indicated by higher CO_2 mineralization and FLF. Drinkwater (1996) concluded that soils managed differently may have similar levels of total SOC but different N mineralization potentials, suggesting differences in soil OM quality. This was clearly the case between basins and rows whereby rows receiving only N-poor crop residues had higher C stability but similar N supply than basins that typically received N-rich and relatively labile compost.

5. Conclusions

The digging and inadvertently moving of planting stations has a detrimental effect on soil C stability as well as N availability, but the additions of compost compensate for these C losses. Similar dynamics of N mineralization in rows that only received low-N crop residues compared to basins that received high-N compost demonstrates the potential for a combination of no-tillage and crop residue retention to improve N availability in CF. The greater C stability in rows compared to basins suggest further exploration of low-quality organic amendments for carbon sequestration and long-term accrual of stable SOC. Further studies should investigate the long-term influence of soil amendment added in basins and rows on C stability under CF beyond ten years.

REFERENCES

Barrios, E., Buresh, R.J., Sprent, J.I. 1996a. Organic matter in soil particle size and density fractions from maize and legume cropping systems. Soil Biology and Biochemistry 28, 185-193.

Barrios, E., Buresh, R.J., Sprent, J.I. 1996b. Nitrogen mineralization in density fractions of soil organic matter from maize and legume cropping systems. Soil Biology and Biochemistry 28, 1459–1465.

Bationo, A., Kihara, J., Vanlauwe, B., Waswa, B., Kimetu, J. 2007. Soil organic carbon dynamics, functions and management in West African agro-ecosystems. Agroforestry Systems 94, 13-25.

Bremner, J.M. 1965. Inorganic forms of nitrogen, pp. 1179-1237. In: C.A. Black, D.D.

Evans, J.L. White, I.E. Ensminger, and F.E. Clark (eds.), Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. American Society of Agronomy, Madison, WI.

Burket, J.Z., Dick, R.P. 1998. Microbial and soil parameters in relation to N mineralization in soils of diverse genesis under differing management systems. Biology & Fertility Soils 27,430–438.

Cambardella, C.A., Elliott, E.T. 1994. Carbon and Nitrogen Dynamics of Soil Organic Matter Fractions from Cultivated Grassland Soils, Soil Science Society of America Journal 58, 123–130.

Carter, M.R., Angers, D.A., Gregorich, E.G., Bolinder, M.A. 1997. Organic carbon storage and nitrogen stocks and storage profiles in cool, humid soils of eastern Canada. Canadian Journal of Soil Science 77, 205–210.

Cauldwell, A.E., Zieger, U. 2000. A reassessment of the fire-tolerance of some miombo woody species in the Central Province, Zambia. African Journal of Ecology 38, 138–146.

Chidumayo, E.N. 1987. Species structure in Zambian Miombo Woodland. Journal of Tropical Ecology 3, 109-118.

Chiwele, D., McKenzie, J. 1996. "Zambia: Agricultural Sector Performance Analysis." University of Zambia, Institute for African Studies.

Dalal, R.C., Henderson, P.A., Glasby, J.M. 1991. Organic matter and microbial biomass in a vertisol after 20-yr of zero-tillage. Soil Biology and Biochemistry 23, 435–441.

Dalal, R.C. 2011. Soil nitrogen and nitrogen-use efficiency under long-term no-till practice. Soil Science Society of America journal 75, 2251-2261.

DeGryze, S., Six, J., Paustian, K., Morris, S.J., Paul, E.A., Merckx, R. 2004. Soil organic carbon pool changes following land-use conversions. Global Change Biology 10, 1120–1132.

Denef, K., Six, J., Merckx, R., Paustian, K. 2004. Carbon sequestration in microaggregates of no-tillage soils with different clay mineralogy. Soil Science Society of America Journal 68, 1935-1944.

Drinkwater, L.E., Cambardella, C.A., Reeder, J.D., Rice, C.W. 1996. Potentially mineralizable nitrogen as an indicator of biologically active soil nitrogen. In: Doran, J.W., Jones, A.J., editors. Methods for assessing soil quality, SSSA Special Publication. Soil Science Society of America 49, 217–29.

FAO, 2008. Investing in sustainable agricultural intensification. The role of conservation agriculture. A framework for action. Food and Agriculture Organization of the United Nations, Rome.

Feller, C., Beare, M.H. 1997. Physical control of soil organic matter dynamics in the tropics. Geoderma 79, 69–116.

Franzluebbers, A.J., Arshad, M.A. 1997. Particulate organic carbon content and potential mineralization as affected by tillage and texture. Soil Science Society of America Journal 61, 1382–1386.

Franzluebbers, A.J., Stuedemann, J.A. 2002. Particulate and non-particulate fractions of soil organic carbon under pastures in the Southern Piedmont USA. Environmental Pollution 116, 53-62.

Gentile, R., Vanlauwe, B., Chivenge, P., Six, J. 2008. Interactive effects from combining fertilizer and organic residue inputs on nitrogen transformations. Soil Biology and Biochemistry 40, 2375–2384.

Gentile, R., Vanlauwe, B., Kavoo, A., Chivenge, P., Six, J. 2010. Residue quality and N fertilizer do not influence aggregate stabilization of C and N in two tropical soils with contrasting texture. Nutrient Cycling in Agroecosystems 88, 121-131.

Gentile, R., Vanlauwe, B., Six, J. 2011. Litter quality impacts short but not long-term soil carbon dynamics in soil aggregate fractions. Ecological Applications 21, 695–703.

Giller, K.E., Witter, E., Corbeels, M., Tittonell, P. 2009. Conservation agriculture and smallholder farming in Africa: The heretics' view. Field Crops Research 114, 23-34.

Glaser, B., Lehmann, J., Fuhrboter, M., Solomon, D., Zech, W. 2001. Carbon and nitrogen mineralization in cultivated and natural savanna soils of Northern Tanzania. Biology and fertility of soils 33, 301-309.

Golchin, A., Oades, J.M., Skjemstad, J.O., Clarke, P. 1994. Soil structure and carbon cycling. Australian Journal of Soil Research 32, 1043–1068.

Gulde, S., Chung, H., Amelung, W., Chang C., Six, J. 2008. Soil carbon saturation controls labile and stable carbon pool dynamics. Soil Science Society of America Journal 72, 605–612.

Haggblade, S., Tembo, G. 2003. Conservation farming in Zambia. EPTD Discussion Paper. Environment and Production Technology Division, International Food Policy Research Institute.

Hobbs, P.R. 2007. Conservation agriculture: what is it and why is it important for future sustainable food production? Journal of Agricultural Science 145, 127- 137.

Jarecki, M.K., Lal, R. 2003. Crop management for soil carbon sequestration. Critical Reviews in Plant Sciences 22, 471–502.

Juo, A.S., Franzluebbers, K., Dabiri, A., Ikhile, B. 1996. Soil properties and crop performance on a kaolinitic Alfisol after 15 years of fallow and continuous cultivation. Plant Soil 180, 209–217.

Kettler, T.A., Doran, J.W. Gilbert, T.L. 2001. Simplified method for soil particle-size determination to accompany soil-quality analyses. Soil Science Society of America Journal 65, 849-82.

Kimetu, J.M., Lehmann, J., Ngoze, S.O., Mugendi, D.N., Kinyangi, J.M., Riha, S., Verchot, L., Recha, J.W., Pell, A.N. 2008. Reversibility of soil productivity decline with organic matter of differing quality along a degradation gradient. Ecosystems 11, 726-739.

Kimetu, J.M., Lehmann, J. 2010. Stability and stabilization of biochar and green manure in soil with different organic carbon contents. Australian Journal of Soil Research 48, 577-585.

Lal, R., 1997. Residue management, conservation tillage and soil restoration for mitigating greenhouse effect by CO2-enrichment. Soil and Tillage Research 43, 81–107.

Lai, R. 2007. Managing Soils for Food Security and Climate Change. Journal of Crop Improvement 19, 49-71.

Lehmann, J., Poidy, N., Schroth, G., Zech, W. 1998. Short-term effects of soil amendment with legume tree biomass on carbon and nitrogen in particle size fractions in central Togo, Soil Biology and Biochemistry 30, 1545-1552.

Lehmann J., Cravo, M.S., Zech, W. 2001. Organic matter stabilization in a Xanthic Ferralsol of the central Amazon as affected by single trees: chemical characterization of density, aggregate, and particle size fractions. Geoderma 99, 147–68.

Lewis, D., Bell, S., Fay, J., Bothi, K.L., Gatere, L., Kabila, M., Mukamba, M., Matokwani, E., Mushimbalume, M., Moraru, C., Lehmann, J., Lassoie, J., Wolfe, D., Lee, D., Buck, L., Travis, A. 2011. Community Markets for Conservation

(COMACO) links biodiversity conservation with sustainable improvements in livelihoods and food production. PNAS 108, 13957 –13962.

Lobe, I., Amelung, W., Du Preez, C.C. 2001. Losses of carbon and nitrogen with prolonged arable cropping from sandy soils of the South African Highveld. European Journal of Soil Science 52, 93–101.

Mann, L., Tolbert, V., Cushman, J. 2002. Potential environmental effects of corn (Zea mays L.) stover removal with emphasis on soil organic matter and erosion. Agriculture, Ecosystems and Environment 89, 149–166.

Marongwe, L. S., Kwazira, K., Jenrich, M., Kassam, A., Friedrich, T. 2011. An African success, the case of conservation agriculture in Zimbabwe. International Journal of Agricultural Sustainability 9, 153–161.

Mateete, B., Sanginga, N., Woomer, P.L. 2010. Restoring soil fertility in sub-Sahara Africa. In Advances in Agronomy 108, 183-236.

Moran, K.K., Six, J., Horwath, W.R., van Kessel, C. 2005. Role of mineral-nitrogen in residue decomposition and stable soil organic matter formation. Soil Science Society of American Journal 69, 1730–1736.

Munyati, C. 2000. Wetland change detection on the Kafue Flats, Zambia, by classification of a multi-temporal remote sensing image dataset. International Journal of Remote Sensing 21, 1787-1806.

Neill, C., Piccolo, M.C., Steudler, P.A., Melillo, J.M., Feigl, B.J., Cerri, C.C. 1995. Nitrogen dynamics in soils of forests and native pastures in western Brazilian Amazon Basin. Soil Biology and Biochemistry 27, 1167–1175.

Palm, C.A., Gachengo, C.N., Delve, R.J., Cadisch, G., Giller, K.E. 2001. Organic inputs for soil fertility management in tropical agro-ecosystems: application of an organic resource database. Agriculture Ecosystems and Environment 83, 27–42.

Pandey, C.B., Begum, M., 2010. The effect of a perennial cover crop on net soil N mineralization and microbial biomass carbon in coconut plantations in the humid tropics. Soil Use and Management 26, 158–166.

Paustian, K., Collins, H.P., Paul, E.A. 1997. Management controls on soil carbon. In: Paul, E.A., Paustian, K., Elliott, E.T., Cole, C.V. Eds. Soil Organic Matter in Temperate Ecosystems: Long-Term Experiments in North America. CRC Press, New York, pp. 15–49.

Puget, P., Chenu, C., Balesdent, J. 1995. Total and young organic matter distributions in aggregates of silty cultivated soils. European Journal of Soil Science 46, 449-459.

Sa, J.C.M., Cerri, C.C., Dick, W.A., Lal, R., Venske, F.S.P., Piccolo, M.C., Feigl, B.E. 2001. Organic matter dynamics and carbon sequestration rates for a tillage chronosequence in a Brazilian Oxisol. Soil Science Society of America Journal 65, 1486-1499.

Sa, J.C.M., Cerri, C.C., Lal, R., Dick, W.A., Piccolo, M.C., Feigl, B.E. 2009. Soil organic carbon and fertility interactions affected by a tillage chronosequence in a Brazilian Oxisol. Soil and Tillage Research 104, 56–64.

Shetto, R., Owenya, M. 2007. Conservation Agriculture as Practised In Tanzania: Three Case Studies. African Conservation Tillage Network, Centre de Coopération Internationale de Recherche Agronomique pour le Développement, Food and Agriculture Organization of the United Nations, Nairobi, Kenya.

Six, J., Elliot, E.T., Paustian, K. 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture.
Soil Biology and Biogeochemistry 32, 2099–2103.

Six, J., Feller, C., Denef, K., Ogle, S.M., de Moraes, J.C., Albrecht, A. 2002. Soil organic matter, biota and aggregation in temperate and tropical soils – effects of no-tillage. Agronomie 22, 755–775.

Sohi, S.P., Mahieu, N., Arah, J.R.M., Powlson, D.S., Madari, B., Gaunt, J.L. 2001. A procedure for isolating soil organic matter fractions suitable for modeling. Soil Science Society of America journal 65, 1121-1128.

Solomon, D., Lehmann, J., Kinyangi, J., Amelung, W., Lobe, I., Pell, A., Riha, S., Ngoze, S., Verchot, L., Mbugua, D., Skjemstad, J., Schafer, T. 2007. Long-term impacts of anthropogenic perturbations on dynamics and speciation of organic carbon in tropical forest and subtropical grassland ecosystems. Global Change Biology 13, 511–530.

Stockfisch, N., Forstreuter, T., Ehlers W. 1999. Ploughing effects on soil organic matter after twenty years of conservation tillage in Lower Saxony, Germany. Soil Tillage and Research 52, 91-101.

Strotmann, U., Reuschenbach, P., Schwarz, H., Pagga U. 2004. Development and evaluation of an online CO_2 evolution test and a multicomponent biodegradation test system. Applied and Environmental Microbiology 70, 4621-4628.

Tan, Z., Lal, R., Owens, L., Izaurralde, R.C. 2007. Distribution of light and heavy fractions of soil organic carbon as related to landuse and tillage practice. Soil and Tillage Research 92, 53–59.

Taok, M., Nelly, C., Andre, P., Schoefs, O., 2007. Monitoring of microbial activity in soil using biological oxygen demand measurement and indirect impedancemetry. European journal of soil biology 43, 335-340.

Von Lutzon, M., Leifeld, J., Kainz, M., Kogel-Knabner, I., Munch, J.C. 2000. Indications for soil organic matter quality in soils under different management. Geoderma 105, 243–258.

Yang, X.M., Wander, M.M. 1999. Tillage effects on soil organic carbon distribution and storage in a silt loam soil in Illinois. Soil Tillage and Research 52, 1–9.

Zech, W., Senesi N., Guggenberger, G., Kaiser, K., Lehmann, J., Miano, T.M., Miltner, A., Schroth, G. 1997. Factors con-trolling humification and mineralization of soil organic matter in the tropics. Geoderma 79, 117–161.

Zingore, S., Manyame, C., Nyamugafata, P., Giller, K.E. 2005. Long-term changes in organic matter of woodland soils cleared for arable cropping in Zimbabwe, European Journal of Soil Science 56, 727–736.

APPENDIX A

Supplementary information

Table 1.S1a. Correlation coefficients between TF grain yield and soil, environmental variables and management variables with a significance level of p≤0.05.

Farming System	Soil Properties			Site Variables		Management Variables		
	PC1	PC2	PC3	PC1	PC2	PC1	PC2	PC3
All sites	0.004ns	0.01ns	−0.01ns	0.03ns	0.06***	0.05**	0.01ns	0.002ns
AEZ I	0.03ns	0.003ns	0.0003ns	0.04ns	−0.06ns	−0.18**	0.01ns	0.01ns
AEZ II	0.02ns	0.01ns	0.02ns	0.01ns	0.04ns	−0.03ns	0.001ns	−0.01ns
AEZ III	0.23*	0.02ns	−0.13ns	0.001ns	0.001ns	−0.002ns	−0.01ns	n/a

Table 1.S1b. Correlation coefficients between CF grain yield and soil, environmental variables and management variables with a significance level of p≤0.05. n/a data not available

Farming System	Soil Properties			Site Variables		Management Variables		
	PC1	PC2	PC3	PC1	PC2	PC1	PC2	PC3
All sites	0.05***	0.05***	−0.0002ns	−0.0002ns	−0.01ns	−0.05**	−0.002ns	−0.004ns
AEZ I	0.01ns	0.04ns	0.03ns	0.04ns	−0.08ns	0.01ns	0.0004ns	0.0003ns
AEZ II	−0.002ns	0.001ns	0.0002ns	0.003ns	−0.0001ns	0.4ns	0.01ns	0.01ns
AEZ III	−0.09ns	−0.01ns	0.03ns	0.10ns	0.25*	−0.01ns	0.05ns	0.05ns

Table 1.S2a. Correlation coefficients between CF grain yield with soil, site and management variables with a significance level P≤0.05. Soil texture percent silt + clay >50%.

Farming System	Soil Properties			Site Variables			Management Variables		
	PC1	PC2	PC3	PC1	PC2	PC3	PC1	PC2	PC3
All sites	0.02ns	0.01ns	0.05ns	0.06ns	0.08ns	0.0001ns	n/a	n/a	n/a
AEZ I	0.10ns	0.09ns	0.08ns	0.01ns	0.001ns	0.002ns	0.0001ns	0.0001ns	0.01ns
AEZ II	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
AEZ III	0.02ns	0.01ns	0.25ns	0.20ns	0.29ns	n/a	0.01ns	0.05ns	0.15ns

Table 1.S2b. Correlation coefficients between CF grain yield with soil, site and management variables with a significance level P≤0.05. Soil texture percent silt + clay <50%.

Farming System	Soil Properties			Site Variables			Management Variables		
	PC1	PC2	PC3	PC1	PC2	PC3	PC1	PC2	PC3
All sites	0.06**	0.01ns	0.002ns	0.05*	0.002ns	0.001ns	n/a	n/a	n/a
AEZ I	0.05ns	0.05ns	0.01ns	0.04ns	0.06ns	0.01ns	0.18**	0.01ns	0.01ns
AEZ II	0.02ns	0.003ns	0.002ns	0.01ns	0.04ns	0.0001ns	0.02ns	0.000001ns	0.002ns
AEZ III	0.01ns	0.06ns	0.35ns	0.08ns	0.001ns	0.01ns	0.14ns	0.003ns	n/a

Table 1.S2c. Correlation coefficients between TF grain yield with soil, site and management variables with a significance level P≤0.05. Soil texture percent silt + clay >50%.

Farming System	Soil Properties			Site Variables			Management Variables		
	PC1	PC2	PC3	PC1	PC2	PC3	PC1	PC2	PC3
All sites	0.001ns	0.07ns	0.1*	0.02ns	0.04ns	0.001ns	n/a	n/a	n/a
AEZ I	0.04ns	0.02ns	0.09ns	0.02ns	0.06ns	0.08*	0.16**	0.01ns	0.01ns
AEZ II	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
AEZ III	0.60ns	0.13ns	0.07ns	0.09ns	0.03ns	n/a	0.01ns	0.02ns	n/a

Table 1.S2d. Correlation coefficients between TF grain yield with soil, site and management variables with a significance level P≤0.05. Soil texture percent silt + clay <50%

Farming System	Soil Properties			Site Variables			Management Variables		
	PC1	PC2	PC3	PC1	PC2	PC3	PC1	PC2	PC3
All sites	0.04*	0.001ns	0.01ns	0.01ns	0.01ns	0.0003ns	n/a	n/a	n/a
AEZ I	0.06ns	0.21*	0.01ns	0.08ns	0.15*	0.14ns	0.01ns	0.001ns	0.0004ns
AEZ II	0.02ns	0.0001ns	0.03ns	0.01ns	0.0001ns	n/a	0.04ns	0.01ns	0.01ns
AEZ III	0.21ns	0.03ns	0.17ns	0.10ns	0.001ns	0.20ns	0.45*	0.10ns	0.13ns

Table 2.S1a. Total nutrient uptake as a function of soil properties along the environmental gradient and quality of organic matter additions. (n=284; *P*<0.05).

			Total uptake (kg ha-1)				
AEZ	Treatment	Soil properties	N	P	K	Ca	Mg
1	Control	N g kg^{-1}	39.23	10.21	24.11	1.94	4.15
1	Manure	N g kg^{-1}	48.97	10.14	25.92	¯2.41	4.84
1	Manure + Fertilizer	N g kg^{-1}	86.05	16.48	41.41	¯3.62	7.0
1	Biochar + Fertilizer	N g kg^{-1}	73.11	¯16.86	38.7	3.18	6.62
2	Control	N g kg^{-1}	23.55	6.17	13.82	1.0	2.52
2	Manure	N g kg^{-1}	26.16	5.29	14.52	1.28	2.987
2	Manure + Fertilizer	N g kg^{-1}	¯73.38	12.43	¯34.15	2.79	5.67
2	Biochar + Fertilizer	N g kg^{-1}	¯60.33	¯14.03	¯36.79	3.07	¯6.76
3	Control	N g kg^{-1}	¯64.86	¯10.67	¯26.37	¯2.41	¯5.86
3	Manure	N g kg^{-1}	¯56.18	¯8.79	25.06	2.7	¯5.66
3	Manure + Fertilizer	N g kg^{-1}	¯140.15	¯21.35	¯51.85	4.85	¯11.35
3	Biochar + Fertilizer	N g kg^{-1}	¯132.38	¯20.24	¯53.28	¯4.03	¯12.15
1	Control	C g kg^{-1}	39.23	10.21	24.11	1.94	4.15
1	Manure	C g kg^{-1}	49.0	10.14	25.92	¯2.41	4.84
1	Manure + Fertilizer	C g kg^{-1}	86.05	16.48	41.41	¯3.62	6.99
1	Biochar + Fertilizer	C g kg^{-1}	¯73.11	¯16.86	¯38.7	¯3.18	¯6.62

Table 2.S1a cont'd

AEZ	Treatment	Soil properties	Total uptake (kg ha-1)				
			N	P	K	Ca	Mg
2	Control	C g kg^{-1}	¯23.55	6.17	13.82	0.969	2.52
2	Manure	C g kg^{-1}	26.16	5.29	14.52	1.28*	2.99
2	Manure + Fertilizer	C g kg^{-1}	¯73.38	12.43	¯34.15	¯2.79	5.67
2	Biochar + Fertilizer	C g kg^{-1}	¯60.33	¯14.03	36.79	3.07	¯6.76
3	Control	C g kg^{-1}	¯64.86	¯10.67	¯26.37	¯2.41	¯5.86
3	Manure	C g kg^{-1}	¯56.18	¯8.79	¯25.06	2.7	¯5.66
3	Manure + Fertilizer	C g kg^{-1}	¯140.15	¯21.35*	¯51.85	4.85	¯11.35
3	Biochar + Fertilizer	C g kg^{-1}	¯132.38	¯20.24	¯53.28	¯4.02	¯12.15
1	Control	pH	41.4	10.8	25.88	2.1	4.4
1	Manure	pH	53.34	10.53	28.09	2.57	5.23
1	Manure + Fertilizer	pH	¯94.51	¯17.8	45.92	3.94	7.7
1	Biochar + Fertilizer	pH	¯75.41	17.79	41.06	3.36	6.91
2	Control	pH	22.67	5.98	13.44	0.95*	2.43
2	Manure	pH	27.11	5.49*	14.86	1.34	3.07
2	Manure + Fertilizer	pH	¯74.06	¯13.17	34.31	2.66*	5.87
2	Biochar + Fertilizer	pH	¯61.66	¯14.44	¯35.82	¯3.12	¯6.9
3	Control	pH	64.32	10.82	26.25	¯2.4	5.9
3	Manure	pH	55.42	8.54	24.19	2.72	5.6
3	Manure + Fertilizer	pH	139.15	21.74	50.85	4.48	11.21
3	Biochar + Fertilizer	pH	142.63	21.15	56.34	¯4.41	¯12.96

Table 2.S1a cont'd

AEZ	Treatment	Soil properties	Total uptake (kg ha-1)				
			N	P	K	Ca	Mg
1	Control	Silt clay (percent)	41.6	10.67	25.17	2.02	4.34
1	Manure	Silt clay (percent)	50.7	10.64	26.82	2.51	5.02
1	Manure + Fertilizer	Silt clay (percent)	86.12	16.62	42.46*	3.62	7.13
1	Biochar + Fertilizer	Silt clay (percent)	¯73.09	16.83	38.98	3.16	6.62
2	Control	Silt clay (percent)	¯23.42	6.12	13.89	0.98	2.51
2	Manure	Silt clay (percent)	26.98	¯5.33	15.18	1.35	3.09
2	Manure + Fertilizer	Silt clay (percent)	77.22	12.9	35.49	2.76	5.87
2	Biochar + Fertilizer	Silt clay (percent)	¯62.3	¯14.19	36.45	2.91	6.73
3	Control	Silt clay (percent)	¯64.86	¯10.67	¯26.37	¯2.41	¯5.86
3	Manure	Silt clay (percent)	¯56.18	¯8.79	¯25.06	¯2.7	¯5.7
3	Manure + Fertilizer	Silt clay (percent)	¯138.83	¯21.65	¯51.99	¯4.82	¯11.41
3	Biochar + Fertilizer	Silt clay (percent)	¯139.33	21	56.05	4.29	12.77
1	Control	Available P (mg kg^{-1})	40.95	10.52	24.78	2.0	4.2
1	Manure	Available P (mg kg^{-1})	¯49.33	¯10.37	¯26.22	¯2.44	¯4.87
1	Manure + Fertilizer	Available P (mg kg^{-1})	¯84.82	¯16.38	¯41.73	¯3.57	¯7.01
1	Biochar + Fertilizer	Available P (mg kg^{-1})	¯72.11	¯16.58	38.31	¯3.10	¯6.54
2	Control	Available P (mg kg^{-1})	¯24.53	¯6.33	¯13.5	¯1.0	¯2.53
2	Manure	Available P (mg kg^{-1})	27.03	5.12	13.44	1.13	2.72
2	Manure + Fertilizer	Available P (mg kg^{-1})	80.81	12.65	34.58	2.91	5.83
2	Biochar + Fertilizer	Available P (mg kg^{-1})	¯55.99	12.95	¯33.03	3.0	6.23

Table 2.S1a cont'd

AEZ	Treatment	Soil properties	Total uptake (kg ha-1)				
			N	P	K	Ca	Mg
3	Control	Available P (mg kg^{-1})	¯64.86	¯10.67	¯26.37	¯2.41	¯5.86
3	Manure	Available P (mg kg^{-1})	¯56.18	¯8.79	¯25.06	¯2.7	¯5.66
3	Manure + Fertilizer	Available P (mg kg^{-1})	140.15	21.35	51.85	4.85	11.35
3	Biochar + Fertilizer	Available P (mg kg^{-1})	¯132.38	¯20.24	53.28	4.03	12.15
1	Control	K (mmol kg^{-1})	40.95**	10.52*	24.78*	2.0	4.28*
1	Manure	K (mmol kg^{-1})	49.33*	10.37**	26.22*	2.44	4.87***
1	Manure + Fertilizer	K (mmol kg^{-1})	84.82	16.38	41.73	3.57	7.01
1	Biochar + Fertilizer	K (mmol kg^{-1})	72.1	16.58	38.31	¯3.1	6.54
2	Control	K (mmol kg^{-1})	24.53	6.33	13.5	1.0	2.53
2	Manure	K (mmol kg^{-1})	¯27.03	¯5.12	¯13.44	1.13	¯2.72
2	Manure + Fertilizer	K (mmol kg^{-1})	¯80.81	¯12.65	34.58	2.91*	5.83
2	Biochar + Fertilizer	K (mmol kg^{-1})	¯56.0	12.95	¯33.03	2.9	¯6.23
3	Control	K (mmol kg^{-1})	64.86	10.67	26.37	2.41	5.86
3	Manure	K (mmol kg^{-1})	56.18	8.79*	25.06**	2.7*	5.7
3	Manure + Fertilizer	K (mmol kg^{-1})	140.15	21.35	51.85*	4.85	11.35
3	Biochar + Fertilizer	K (mmol kg^{-1})	132.38	20.24	53.28	¯4.02	¯12.15
1	Control	Na (mmol kg^{-1})	40.95**	10.52	24.78*	2.0*	4.28*
1	Manure	Na (mmol kg^{-1})	49.33	10.37	26.22	¯2.44	4.87
1	Manure + Fertilizer	Na (mmol kg^{-1})	84.82*	16.38	41.73	3.57	7.01
1	Biochar + Fertilizer	Na (mmol kg^{-1})	72.11	¯16.58	¯38.31	¯3.1	¯6.54

Table 2.S1a cont'd

AEZ	Treatment	Soil properties	Total uptake (kg ha-1)				
			N	P	K	Ca	Mg
2	Control	Na (mmol kg^{-1})	¯24.53	¯6.33	¯13.50	1.0	2.53
2	Manure	Na (mmol kg^{-1})	¯27.03	¯5.12	¯13.44	¯1.13	¯2.72
2	Manure + Fertilizer	Na (mmol kg^{-1})	¯80.81	¯12.65*	¯34.58	2.91	¯5.83
2	Biochar + Fertilizer	Na (mmol kg^{-1})	¯56.0	¯12.95	¯33.03	¯3.0	¯6.23
3	Control	Na (mmol kg^{-1})	¯64.86	¯10.67	¯26.37	¯2.41	5.86
3	Manure	Na (mmol kg^{-1})	56.18	8.79	25.06	2.7**	5.66
3	Manure + Fertilizer	Na (mmol kg^{-1})	140.15	21.35	51.85	4.85	11.35
3	Biochar + Fertilizer	Na (mmol kg^{-1})	132.34	20.24	53.28	4.03	12.15
1	Control	Ca (mmol kg^{-1})	40.95	10.52	24.78	2.0	4.28
1	Manure	Ca (mmol kg^{-1})	49.33	10.37	26.22	2.44	4.87
1	Manure + Fertilizer	Ca (mmol kg^{-1})	84.82	16.38	41.73	¯3.57	7.01
1	Biochar + Fertilizer	Ca (mmol kg^{-1})	72.11	¯16.58	¯38.31	¯3.1	¯6.54
2	Control	Ca (mmol kg^{-1})	¯24.53	¯6.33	¯13.5	1.0	2.53
2	Manure	Ca (mmol kg^{-1})	¯27.03	5.12	13.44	1.23	2.72
2	Manure + Fertilizer	Ca (mmol kg^{-1})	¯80.81	12.65	34.58	2.91	5.83
2	Biochar + Fertilizer	Ca (mmol kg^{-1})	¯56.0	12.95	¯33.03	2.9	6.23

Table 2.S1a cont'd

AEZ	Treatment	Soil properties	Total uptake (kg ha-1)				
			N	P	K	Ca	Mg
3	Control	Ca (mmol kg^{-1})	¯64.86	¯10.67	¯26.38	¯2.41	¯5.86
3	Manure	Ca (mmol kg^{-1})	56.18	8.79	25.06	2.695	5.66
3	Manure + Fertilizer	Ca (mmol kg^{-1})	¯140.15	¯21.35	51.85	4.85	11.35
3	Biochar + Fertilizer	Ca (mmol kg^{-1})	132.38	20.24	53.28	¯4.02	12.15
1	Control	Mg (mmol kg^{-1})	40.95	10.52	24.78	1.99	4.28
1	Manure	Mg (mmol kg^{-1})	49.33	10.37	26.22	¯2.44	4.87
1	Manure + Fertilizer	Mg (mmol kg^{-1})	84.82	16.38	41.73	¯3.57	7.01
1	Biochar + Fertilizer	Mg (mmol kg^{-1})	72.11	¯16.58	¯38.31	¯3.1	¯6.54
2	Control	Mg (mmol kg^{-1})	¯24.53	6.33	13.5	1.0	2.53
2	Manure	Mg (mmol kg^{-1})	¯27.03	5.12	13.44	1.13	2.72
2	Manure + Fertilizer	Mg (mmol kg^{-1})	¯80.81	12.65	¯34.58	2.91	¯5.83
2	Biochar + Fertilizer	Mg (mmol kg^{-1})	¯55.99	12.95	¯33.03	2.9	6.23
3	Control	Mg (mmol kg^{-1})	¯64.86	¯10.67	26.37	¯2.41	¯5.86
3	Manure	Mg (mmol kg^{-1})	56.18	8.79	25.06	2.7	5.66
3	Manure + Fertilizer	Mg (mmol kg^{-1})	140.15	21.35	51.85	4.85	11.35
3	Biochar + Fertilizer	Mg (mmol kg^{-1})	132.38	20.24	53.28	4.02***	12.15

Table 2.S1b.Total nutrient uptake as a function of terrain variables along the environmental gradient and quality of organic matter additions. (n=284; *P*<0.05).

			Total uptake (kg ha-1)				
AEZ	Treatment	Environmental co-variates	N	P	K	Ca	Mg
1	Control	Annual precipitation (mm)	39.67	9.37	22.18	1.8	3.88
1	Manure	Annual precipitation (mm)	48.08	9.17	24.75	¯2.19	¯4.53
1	Manure + Fertilizer	Annual precipitation (mm)	87.65	15.79	40.97	3.5	7.01
1	Biochar + Fertilizer	Annual precipitation (mm)	76.51	¯16.12	¯38.35	¯3.11	¯6.42
2	Control	Annual precipitation (mm)	¯23.62	6.2	¯13.73	¯0.96	¯2.5
2	Manure	Annual precipitation (mm)	¯26.06	¯5.35	¯14.23	¯1.27	¯2.93
2	Manure + Fertilizer	Annual precipitation (mm)	¯73.33	¯13.09	¯34.36	¯2.84	¯5.8
2	Biochar + Fertilizer	Annual precipitation (mm)	¯59.85	¯13.9	¯35.95	¯3.16	6.79
3	Control	Annual precipitation (mm)	64.86	10.67	26.37	2.41	5.86
3	Manure	Annual precipitation (mm)	56.18	8.79	25.06	¯2.7	5.66
3	Manure + Fertilizer	Annual precipitation (mm)	140.15	21.35	¯51.85	¯4.85	¯11.35
3	Biochar + Fertilizer	Annual precipitation (mm)	¯132.38	¯20.24	¯53.28	¯4.03	¯12.15

Table 2.S1b cont'd

			Total uptake (kg ha-1)				
AEZ	Treatment	Environmental co-variates	N	P	K	Ca	Mg
1	Control	Elevation (m a.s.l.)	¯40.22***	¯9.46*	¯22.39**	¯1.82*	¯3.93*
1	Manure	Elevation (m a.s.l.)	¯48.08**	¯9.17*	¯24.75*	¯2.19	¯4.53
1	Manure + Fertilizer	Elevation (m a.s.l.)	87.65***	¯15.79*	¯40.97**	¯3.497*	¯7.01**
1	Biochar + Fertilizer	Elevation (m a.s.l.)	¯76.51*	¯16.12	¯38.35	¯3.11	¯6.42
2	Control	Elevation (m a.s.l.)	23.62	6.196	13.73	0.96	2.5
2	Manure	Elevation (m a.s.l.)	26.06	¯5.35	14.23	1.27	¯2.94
2	Manure + Fertilizer	Elevation (m a.s.l.)	73.33	¯13.09	34.36	2.84	5.8
2	Biochar + Fertilizer	Elevation (m a.s.l.)	59.85	13.89	35.95	3.16	6.79
3	Control	Elevation (m a.s.l.)	¯64.86*	¯10.67	¯26.37*	¯2.41	¯5.86*
3	Manure	Elevation (m a.s.l.)	56.18	¯8.79	¯25.06	2.695	¯5.7
3	Manure + Fertilizer	Elevation (m a.s.l.)	¯140.15	¯21.35	¯51.85	4.85	¯11.35
3	Biochar + Fertilizer	Elevation (m a.s.l.)	¯132.38	¯20.24	¯53.28	4.03	¯12.15
1	Control	Slope gradient (degrees)	¯39.38	¯9.55	¯22.68	¯1.86	¯3.98
1	Manure	Slope gradient (degrees)	¯48.89	¯9.28	¯25.12	2.24	¯4.6
1	Manure + Fertilizer	Slope gradient (degrees)	¯89.12	¯16.07	¯41.46	3.56	¯7.15
1	Biochar + Fertilizer	Slope gradient (degrees)	¯75.62*	¯16.16	¯38.1	3.15	¯6.46
2	Control	Slope gradient (degrees)	23.62	¯6.196	13.73	0.96	2.5
2	Manure	Slope gradient (degrees)	26.06	5.35	14.23	1.27	2.94
2	Manure + Fertilizer	Slope gradient (degrees)	¯73.33	¯13.09	34.36	2.84	¯5.799
2	Biochar + Fertilizer	Slope gradient (degrees)	¯59.85	13.89	35.95	¯3.16	¯6.79

Table 2.S1b cont'd

			Total uptake (kg ha-1)				
AEZ	Treatment	Environmental co-variates	N	P	K	Ca	Mg
3	Control	Slope gradient (degrees)	¯64.86	¯10.67	26.37	2.41	5.86
3	Manure	Slope gradient (degrees)	56.18	8.79	25.06	2.695*	5.66
3	Manure + Fertilizer	Slope gradient (degrees)	140.15	21.35	51.85	4.85	11.35
3	Biochar + Fertilizer	Slope gradient (degrees)	132.38	20.24	53.28	¯4.03	12.15
1	Control	Aspect	39.76	9.66	22.87	1.87	4.01
1	Manure	Aspect	¯48.18	¯9.34	25.24	2.23	4.62
1	Manure + Fertilizer	Aspect	88.98	16.09	41.76	3.57	7.14
1	Biochar + Fertilizer	Aspect	76.81	16.43	39.08	3.18	6.55
2	Control	Aspect	¯23.62	¯6.196	¯13.73	¯0.96	¯2.5
2	Manure	Aspect	¯26.06	¯5.35	¯14.23	¯1.27	¯2.94
2	Manure + Fertilizer	Aspect	¯73.33	¯13.09	¯34.36	2.84	5.8
2	Biochar + Fertilizer	Aspect	¯59.85	¯13.89	¯35.95	3.16	6.79
3	Control	Aspect	64.86	10.67	26.37	2.41**	5.86
3	Manure	Aspect	¯56.18	8.79	25.06	¯2.70	¯5.66
3	Manure + Fertilizer	Aspect	140.15	21.35	51.85	4.85	11.35
3	Biochar + Fertilizer	Aspect	¯132.38	20.24	53.28	¯4.03	¯12.15

***, **, *: significant at P<0.001, 0.01, 0.05, respectively, n=284

Principal component analysis for AEZ I

In order to group the correlated soil properties, environmental co-variates and terrain variables to the smallest possible subsets representing the majority of variation, PCA was performed to individual AEZs to better quantify relationship with yield and total nutrient uptake. In the drier region (AEZ I), PCA identified seven PC loadings with eigenvalue >1 (Table S2a) which were retained to quantify correlation with yield and total plant nutrient uptake. These PCs explained 82 % of the total sample variance. The variables that explained 82 % of the variation are C, N, P, Ca, Na, Mn, S, Zn, elevation, pH, aspect, absolute, plan and profile curvature were explained by the seven PCs.

The first and the most important factor, which explained 27% of the variation, had the highest eigenvalue and variables with large positive loadings (Table S.2a). The high loadings (>0.65) were soil C, N, Ca, Mg and Mn and termed as *soil fertility factor*. PC2 collectively explained 16 % of the sample variance and was termed as *texture factor* because of high positive loadings in silt-clay, Na, S and high negative loadings in elevation indicating low change in altitude or slope gradient. PC3 was termed as *curvature factor* because of high positive loadings for absolute and plan curvature, and high negative loadings for profile curvature. PC4 was termed as *pH factor* because of high positive loadings for pH and low negative loadings for Fe. Iron content was negatively correlated with pH and Fe availability is known to decrease as pH increases (Moraghan and Mascagni, 1991). PC6 was regarded to as *Soil P* factor because of high positive loadings in P and low negative loadings in slope gradient.

Table 2.S2a. Rotated loadings of measured variables of AEZ I for the seven factors with eigenvalues >1.0.

Variables	Soil fertility PC1	Texture PC2	Curvature PC3	pH PC4	Aspect PC5	Soil P PC6	Zinc PC7
Eigen value	6.75	3.31	2.13	1.58	1.40	1.10	1.01
Variance	5.6	3.2	2.8	1.5	1.5	1.3	1.3
Cumulative percent	26.5	41.9	55.4	62.7	69.8	76.2	82.3
pH	0.13	0.14	-0.31	**0.76**	-0.25	0.17	0.02
Siltclay	0.10	**0.70**	0.10	0.10	0.01	0.34	0.27
N	**0.91**	0.19	-0.11	-0.06	0.11	0.09	0.01
C	**0.93**	0.11	-0.11	-0.07	0.08	0.05	0.03
Ca	**0.94**	0.13	-0.07	0.06	-0.01	0.01	0.03
P	-0.03	-0.08	0.06	0.04	0.15	**0.82**	0.11
Mg	**0.94**	0.09	-0.13	-0.03	-0.08	-0.03	0.10
K	**0.58**	0.29	0.07	0.15	0.35	0.34	0.00
Na	0.34	**0.85**	-0.07	-0.08	-0.01	-0.08	-0.06
Fe	0.40	0.23	-0.35	**-0.48**	0.10	0.22	0.22
Zn	0.01	-0.03	-0.04	-0.04	-0.08	0.12	**0.87**
Mn	**0.88**	0.02	-0.01	0.07	-0.18	-0.09	-0.02
Cu	**0.48**	0.41	0.18	0.36	0.28	0.08	-0.24
S	-0.06	**0.91**	0.02	-0.09	0.01	-0.05	-0.16
Rainfall	0.32	**0.45**	0.08	0.35	0.36	-0.10	**0.45**
Elevation	-0.37	**-0.69**	-0.03	-0.24	-0.37	0.15	-0.19
Slope gradient	-0.42	-0.32	-0.12	0.53	0.25	**-0.51**	0.14
Aspect	-0.06	0.08	0.15	-0.17	**0.84**	0.15	-0.08
Curvature	-0.10	0.04	**0.96**	-0.13	0.13	0.05	0.00
Curvature profile	0.10	-0.02	**-0.89**	0.17	-0.23	-0.09	-0.10
Curvature plan	-0.05	0.05	**0.85**	0.11	-0.10	0.00	-0.11

High P levels occur in lower slopes or depressions because over the years erosional processes deposit sediments carrying P in these locations. PC5 and PC7 were regarded as *aspect* and *Zinc factor* respectively because of dominant positive loadings for aspect and Zn.

Principal component analysis for AEZ II

In the degraded plateau (AEZ II), PCA identified six PC loadings with eigenvalue >1 (Table S1b) which were retained to quantify correlation with yield and nutrient uptake. These PCs cumulatively explained 80 % of the total variation. PC1 had the highest eigenvalue and explained 25 % of total variation. It was termed as *soil fertility factor* because C, N, K, Ca, Mg and Mn variables contributed with high loadings, while *curvature factor* PC2 was explained by high positive loadings for absolute and plan curvature, and high negative loadings for profile curvature. Relatively large positive and negative curvatures occur in areas of transition on hill slopes and these areas either lose or accumulate soil through erosive processes. PC3 was termed as *texture factor* because Na and S high positive loadings and moderate loadings of rainfall. PC4 was termed as micronutrients factor which had a high positive loadings of Zn and Cu, and moderate loadings of P. PC5 was termed as *slope gradient factor* because of high positive loadings of slope gradient and moderate negative loadings of aspect. PC6 termed as *pH factor* had high positive loadings of pH and high negative loadings of silt-clay as an indication of low clay content.

Table 2.S2b. Rotated loadings of measured variables of AEZ II for the seven factors with eigenvalues >1.0.

Variables	Soil fertility PC1	Curvature PC2	Texture PC3	Micro-nutrients PC4	Slope gradient PC5	pH PC6
Eigen value	6.37	3.06	2.20	1.51	1.31	1.08
Variance	5.3	2.6	2.5	2.1	1.5	1.5
Cumulative Percent	25.4	37.8	49.9	59.8	67.0	73.9
pH	0.21	0.08	0.05	0.08	0.06	**0.79**
Siltclay	0.00	-0.01	0.27	0.21	0.07	**-0.70**
N	**0.88**	0.18	-0.03	0.15	0.16	-0.05
C	**0.88**	0.21	-0.05	0.05	0.13	-0.05
Ca	**0.84**	0.03	-0.07	-0.08	-0.09	0.03
P	0.26	0.04	0.00	**0.53**	0.09	-0.29
Mg	**0.88**	0.04	-0.28	0.08	-0.10	0.15
K	**0.71**	0.01	-0.14	0.52	0.02	0.12
Na	-0.21	0.03	**0.87**	0.23	0.12	-0.10
Fe	**0.63**	-0.04	-0.17	0.05	-0.40	0.02
Zn	0.05	0.22	0.12	**0.70**	-0.21	-0.14
Mn	**0.78**	0.03	-0.16	0.13	0.06	0.31
Cu	0.02	0.08	0.15	**0.84**	0.28	0.22
S	-0.13	-0.08	**0.85**	-0.03	0.16	-0.15
Rainfall	-0.49	-0.02	**0.64**	0.06	-0.22	0.01
Elevation	**-0.61**	0.02	0.51	0.07	0.37	0.07
Slope gradient	-0.05	-0.12	-0.01	0.26	**0.78**	-0.09
Aspect	-0.10	-0.10	-0.35	0.27	**-0.56**	-0.11
Curvature	0.08	**0.97**	0.00	0.09	-0.01	0.05
Curvature profile	-0.09	**-0.90**	0.06	-0.01	0.04	0.02
Curvature plan	0.09	**0.82**	0.02	0.16	0.01	0.08

Principal component analysis for AEZ III

In the wetter region (AEZ III), seven PCs were identified with eigenvalue >1 (Table S1c) that were retained to quantify correlation with yield and nutrient uptake. These PCs cumulatively explained 86 % of the total sample variance. The variables that explained the percent variance are pH, silt-clay, C, N, P, K, Na, Ca, Mg, Mn, Fe, S, rainfall, elevation, absolute, plan and profile curvature Measured variables with relatively high and moderate PC loadings within each factor are indicated on Table S1c. PC1 the most important factor explained 17 % of the variation and had variable loadings with high dominance of Ca and Mg, and moderately highly loadings of C, N and slope gradient, and negative moderate loadings of aspect. It was termed as *soil fertility factor* because of dominant Mg and Ca soil base cations and high loadings of C and N as soil fertility properties, and moderate loadings slope and negative aspect. Soil C and N are strongly correlated with clay content which possess negative charge that attract positively charged Mg and Ca (cations). Cations adsorbed to exchange sites are resistant to downward movement in soils with water. Soil development along a hillslope is determined by slope position on the hillslope, drainage and soil transport (Gerrard, 1981; Pennock and De Jong, 1987; Moore et al., 1993).

PC3 was termed as *curvature factor* because of high positive loadings for absolute and plan curvature, and high negative loadings for profile curvature. PC3 was termed as *soil chemistry factor* because of high K, Na, Mn, and S positive loadings. PC4 was termed as *rainfall factor* because of relatively high positive loadings in elevation. Only other two variables with high negative and positive loadings are rainfall and P respectively. Both of these variables were highly correlated to each other and to elevation. P availability is decreases with increase in rainfall. PC5, PC6 and PC7 were termed as *texture, pH and Fe factor* respectively because of absolute positive dominant loadings in silt-clay, pH and Fe.

Table 2.S2c. Rotated loadings of measured variables of AEZ III for the seven factors with eigenvalues.

Variables	Soil fertility PC1	Curvature PC2	Macro-nutrients PC3	Rainfall PC6	Texture PC5	pH PC6	Fe PC7
Eigen value	5.80	3.49	2.58	2.22	1.56	1.24	1.06
Variance	3.5	3.4	3.3	2.8	1.7	1.7	1.6
Cumulative Percent	16.6	32.6	48.5	61.7	69.9	78.0	85.5
pH	0.11	-0.04	-0.10	0.08	-0.17	**0.89**	-0.13
Siltclay	-0.10	0.09	-0.14	0.04	**0.89**	-0.23	0.10
N	**0.63**	0.11	0.14	0.58	0.05	0.04	-0.43
C	**0.62**	0.08	0.09	0.60	0.06	-0.03	-0.42
Ca	**0.90**	0.13	0.19	0.25	-0.05	0.03	-0.03
P	0.14	0.10	-0.31	**0.68**	-0.41	0.25	0.16
Mg	**0.91**	0.08	0.03	-0.02	0.03	0.16	0.07
K	0.01	-0.25	**0.80**	-0.17	-0.23	0.37	-0.10
Na	0.30	0.02	**0.79**	0.27	0.20	-0.13	-0.02
Fe	-0.03	-0.39	0.20	-0.06	0.10	-0.24	**0.82**
Zn	0.36	0.19	**0.48**	-0.11	0.42	-0.31	-0.30
Mn	0.32	0.11	**0.75**	0.08	-0.25	-0.26	0.04
Cu	-0.23	0.32	0.10	-0.37	**-0.55**	-0.14	0.00
S	-0.09	-0.04	**0.83**	0.21	-0.05	-0.07	0.34
Rainfall	-0.10	-0.19	-0.32	**-0.75**	-0.12	-0.29	0.11
Elevation	0.11	0.11	0.19	**0.77**	0.21	-0.30	0.05
Slope gradient	**0.56**	0.40	0.42	-0.01	0.08	0.25	0.44
Aspect	**-0.54**	0.39	-0.09	-0.19	0.01	0.26	0.07
Curvature	0.08	**0.97**	-0.01	0.12	0.00	-0.04	-0.10
Curvature profile	-0.14	**-0.90**	-0.06	-0.20	-0.06	-0.18	0.16
Curvature plan	0.01	**0.91**	-0.08	0.03	-0.06	-0.22	-0.04

Table 2.S3a. Correlation coefficients for regression of averaged maize yield on factors of 21 soil properties, environmental co-variates and terrain variables in AEZ I.

AEZ	Treatment	Soil fertility PC1	Texture PC2	Curvature PC3	pH PC4	Aspect PC5	Soil P PC6	Zinc PC7
I	Control	0.01	0.09*	0.00001	-0.004	-5.67e-6	0.01	-0.002
I	Manure	0.022	0.022	-0.014	0.002	0.0034	-0.03	-0.004
I	Manure + Fertilizer	0.0004	0.081*	0.012	-0.0003	0.002	-0.01	0.002
I	Biochar + Fertilizer	-0.023	0.01	-0.04	-0.002	-0.0001	0.001	-0.001

***, **, *: significant at $P<0.001$, 0.01, 0.05, respectively, n=284.

Table 2.S3b. Correlation coefficients for regression of averaged maize yield on factors of 21 soil properties, environmental co-variates and terrain variables in AEZ II.

AEZ	Treatment	Soil fertility PC1	Curvature PC2	Texture PC3	Micro-nutrients PC4	Slope gradient PC5	pH PC6
II	Control	0.03	0.0003	0.04	-0.0002	0.01	0.01
II	Manure	-0.0004	0.02	-0.022	-0.001	0.04	0.002
II	Manure + Fertilizer	2.00E-06	0.0002	0.024	-0.024	0.004	0.001
II	Biochar + Fertilizer	0.0004	0.05*	0.031	-0.05*	0.01	-0.01

***, **, *: significant at P<0.001, 0.01, 0.05 respectively, n=284.

Table 2.S3c. Correlation coefficients for regression of averaged maize yield on factors of 21 soil properties, environmental co-variates and terrain variables in AEZ III.

AEZ	Treatment	Soil fertility PC1	Curvature PC2	Soil chemistry PC3	Elevation PC4	Texture PC5	pH PC6	Fe PC7
III	Control	-0.09	0.02	-0.022	-0.08	-0.0001	-0.003	0.002
III	Manure	0.008	0.01	0.09	-0.13	-0.04	0.04	0.001
III	Manure + Fertilizer	-0.28	-0.2	-0.01	0.06	-0.1	0.0003	-0.03
III	Biochar + Fertilizer	-0.11	-0.02	0.01	-0.0003	-0.07	0.004	0.020

***, **, *: significant at P<0.001, 0.01, 0.05, respectively

Table 2.S4a. Correlation coefficients for regression of total plant nutrient uptake on factor of 21 soil properties, environmental co-variates and terrain variables in AEZ I (drier region). ***, **, *: significant at P<0.001, 0.01, 0.05 respectively, n=284

AEZ	Treatment	Nutrient	Soil fertility PC1	Texture PC2	Curvature PC3	pH PC4	Aspect PC5	Soil P PC6	Zinc PC7
I	Control	N	0.01	0.06	-0.001	-0.001	0.001	0.003	-0.003
I		P	0.0002	0.02	-0.013	0.0004	0.02	0.005	0.01
I		K	0.001	0.03	-0.02	0.0002	0.001	0.001	-0.01
I		Ca	-0.0003	0.04	-0.02	0.0005ns	0.0003	1.00E-04	-0.03
I		Mg	1.00E-05	0.05	-0.01	-0.002ns	0.0002	0.01	-0.03
I	Manure	N	0.01	0.007	-0.01	-0.0001	2.00E-07	-0.0003	-0.002
I		P	-0.004	-0.0000002	-0.05	0.01	0.01	-0.004	-0.001
I		K	-0.0003	-0.004	-0.013	0.01	0.01	-0.012	-0.0001
I		Ca	0.0000001	-0.0001	-0.00001	-0.0001	-0.00003	0.0001	-0.001
I		Mg	-0.002	-0.001	-0.02	0.0002	0.002	-0.002	-0.004
I	Manure + Fertilizer	N	-0.0003	-0.003	-0.002	0.01	0.03	-0.03	0.01
I		P	-0.003	-0.001	-0.07*	0.002	0.01	-0.01	0.004
I		K	-0.02	-0.02	-0.13**	0.04	0.05	-0.04	0.03
I		Ca	-0.07*	-0.08	-0.11**	0.65*	0.06	-0.05	0.01
I		Mg	-0.02	-0.005	-0.11**	0.03	0.04	-0.03	0.01
I	Biochar + Fertilizer	N	-0.021	-0.003	0.03	0.013	0.15	-0.02	0.002
I		P	-0.07*	-0.06	-0.09*	0.04	0.05	-0.03	0.01
I		K	-0.12**	-0.08*	-0.11**	0.09**	0.1**	-0.07*	0.01
I		Ca	-0.07*	-0.01	-0.07*	0.02	0.03	-0.01	-0.001
I		Mg	-0.1**	-0.04	-0.09*	0.03	0.05	-0.02	0.004

Table 2.S4b. Correlation coefficients for regression of total plant nutrient uptake on factors of 21 soil properties, environmental co-variates and terrain variables in AEZ II (degraded plateau). ***, **, *: significant at P<0.001, 0.01, 0.05 respectively, n=284.

AEZ	Treatment	Nutrient	Soil fertility PC1	Curvature PC2	Texture PC3	Micro-nutrients PC4	Slope gradient PC5	pH PC6
II	Control	N	0.001	-0.002	0.01	-0.01	0.04	0.01
II		P	0.004	1.00E-04	0.01	-0.02	0.03	0.001
II		K	0.01	0.001	0.02	-0.01	0.04	0.001
II		Ca	0.01	0.003	0.02	-0.01	0.04	0.002
II		Mg	0.01	0.0004	0.01	-0.01	0.03	0.0004
II	Manure	N	0.001	0.04	-0.00002	-0.001	0.04	0.002
II		P	0.02	0.01	-0.003	-0.003	0.05	0.01
II		K	0.02	0.02	-0.001	0.001	0.06*	0.01
II		Ca	0.03	0.01	0.002	0.01	0.04	0.004
II		Mg	0.02	0.01	-0.004	0.02	0.06*	0.01
II	Manure + Fertilizer	N	-0.01	0.004	0.0004	-0.01	0.0001	0.0001
II		P	0.01	-0.0002	-0.01	-0.03	-0.001	0.001
II		K	0.001	0.01	0.01	-0.001	0.02	0.002
II		Ca	0.01	0.004	0.01	0.02	0.01	0.03
II		Mg	0.01	0.003	¯0.00001	-0.01	0.002	0.003
II	Biochar + Fertilizer	N	-0.004	-0.01	0.000002	-0.02	0.003	-0.002
II		P	3.00E-05	0.0001	0.001	-0.01	0.003	0.0003
II		K	-0.003	1.00E-07	1.00E-05	-0.01	0.003	-0.00052
II		Ca	0.01	-0.0001	1.00E-04	-0.01	0.0003	-0.0023
II		Mg	-0.00002	2.00E-04	0.0002	-0.02	0.001	-0.0012

Table 2.S4c. Correlation coefficients for regression of total plant nutrient uptake on factors of 21 soil properties, environmental co-variates and terrain variables in AEZ III (wetter region). ***, **, *: significant at P<0.001, 0.01, 0.05 respectively, n=284.

AEZ	Treatment	Nutrient	Soil fertility PC1	Curvature PC2	Soil chemistry PC3	Elevation PC4	Texture PC5	pH PC6	Fe PC7
III	Control	N	-0.04	0.0003	-0.004	-0.12	-0.09	0.01	-0.04
III		P	-0.03	0.002	-0.01	-0.07	-0.04	0.01	-0.02
III		K	-0.03	0.002	-0.01	-0.16	-0.1	0.01	-0.02
III		Ca	-0.67	0.018	-0.01	-0.12	-0.04	0.01	-0.001
III		Mg	-0.03	0.004	-0.01	-0.14	-0.04	0.02	-0.02
III	Manure	N	0.14	-0.01	0.06	-0.06	-0.04	0.03	0.001
III		P	0.01	-0.01	0.04	-0.08	-0.02	0.08	0.01
III		K	0.01	0.001	0.29**	-0.08	-0.01	0.17	-0.03
III		Ca	0.04	0.001	0.38**	0.01	-0.01	0.01	0.02
III		Mg	0.01	-0.0003	0.1	-0.03	-0.02	0.04	0.01
III	Manure + Fertilizer	N	-0.10	-0.27*	-0.0002	0.02	-0.12	0.0003	-0.47
III		P	-0.07	-0.18	-0.003	0.001	-0.07	0.001	-0.00002
III		K	-0.01	-0.04	0.07	-0.001	-0.03	0.05	0.01
III		Ca	-0.004	-0.02	0.02	0.1	-0.03	1.00E-04	0.003
III		Mg	-0.02	-0.12	0.0001	0.01	-0.06	0.001	-0.001
III	Biochar + Fertilizer	N	-0.04	-0.14	0.003	-0.02	-0.07	-0.001	-0.02
III		P	-0.001	-0.11	0.0002	-0.01	-0.001	0.02	0.01
III		K	-0.07	-0.03	0.0003	3.00E-05	-0.01	0.0002	0.01
III		Ca	0.15	0.17	-0.08	0.20*	-0.07	-0.23*	-0.07
III		Mg	-0.07	-0.18	-0.05	0.01	-0.04	-0.07	-0.01

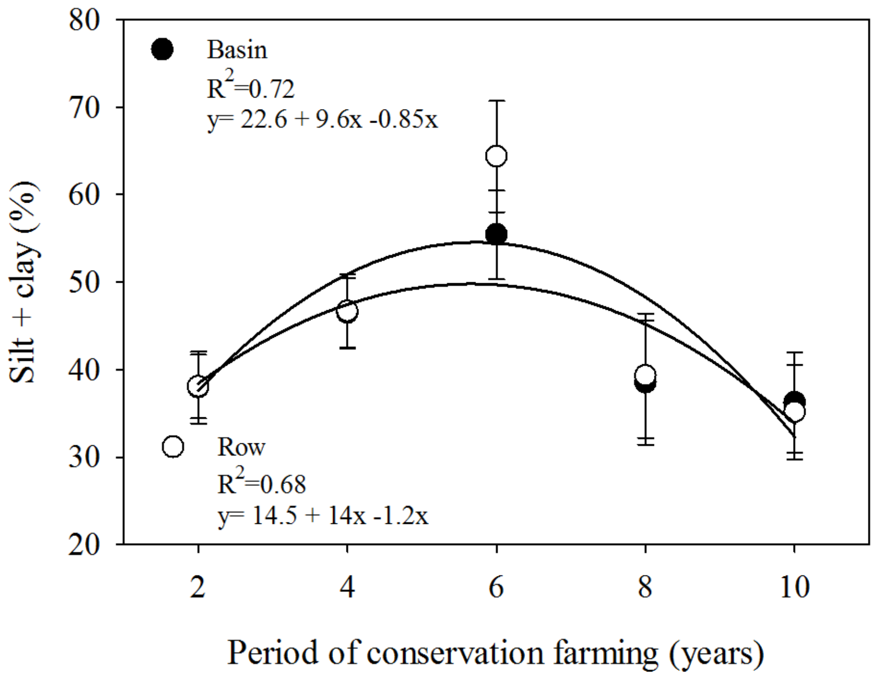

Figure 3.S1. Dynamics in percent silt + clay content over the period of conservation farming practices.

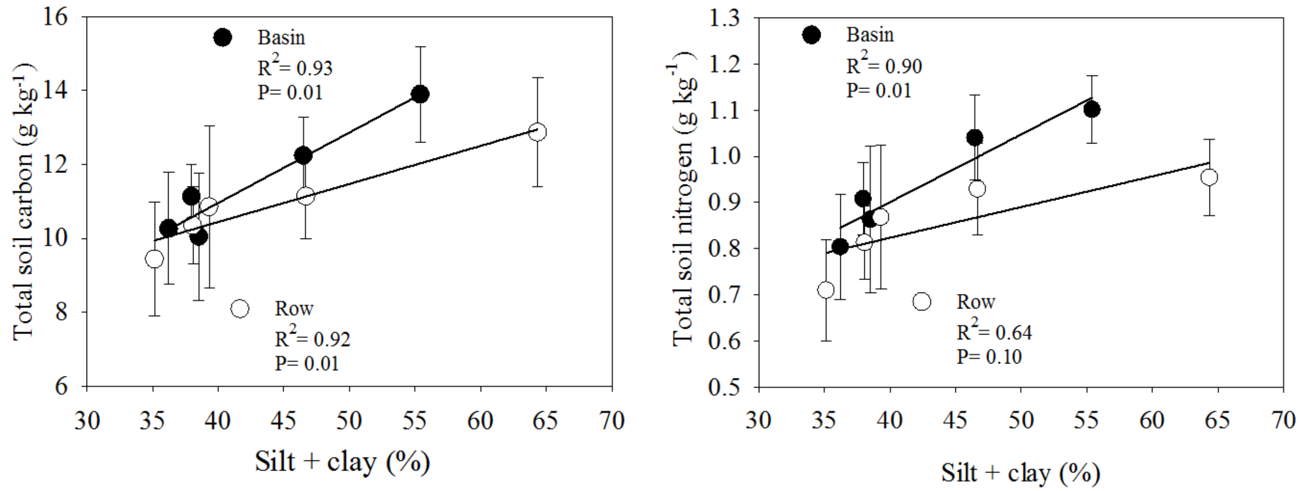

Figure 3.S2. Correlation between total soil carbon and nitrogen with texture during the chronosequence period. Vertical bars represent standard error, n=10.

Accompanying data in figures

Data table for chapter 1, Figure 1.1

	X coordinates	Y coordinates
	(decimal degrees)	
North West	31.19188889	-10.95046944
North East	33.63661944	-10.94436111
South East	33.21853611	-14.04138333
South West	30.14034167	-14.00793889

Data table for chapter 1, Figure 1.2a

Cumulative rainfall (October 2007 to April 2008)						
Months	AEZ I	SE	AEZ II	SE	AEZ III	SE
October	0	0.00	21	4.60	7	0.12
November	76	1.00	49	7.49	58	1.36
December	128	2.88	196	5.17	293	2.90
January	174	1.95	324	11.27	442	2.95
February	61	2.39	232	3.83	372	3.58
March	23.5	1.61	31	6.14	152	4.14
April	0	0.00	21	4.80	41	2.97

Data table for chapter 1, Figure 1.2b

Date	AEZ I	AEZ II	AEZ III	Date	AEZ I	AEZ II	AEZ III
1	0	0	4	32	0	21	7
2	0	0	7	33	10	21	7
3	0	0	7	34	10	24	7
4	0	0	7	35	10	24	7
5	0	0	7	36	10	28	7
6	0	0	7	37	20	28	7
7	0	0	7	38	20	36	7
8	0	0	7	39	30	37	7
9	0	0	7	40	46	37	7
10	0	3	7	41	48	39	7
11	0	3	7	42	51	45	7
12	0	3	7	43	51	55	7
13	0	3	7	44	51	55	38
14	0	3	7	45	51	56	47
15	0	3	7	46	54	62	80
16	0	6	7	47	54	65	80
17	0	6	7	48	54	67	80
18	0	8	7	49	71	67	80
19	0	10	7	50	91	67	124
20	0	11	7	51	91	69	134
21	0	11	7	52	110	69	134
22	0	11	7	53	110	70	134
23	0	11	7	54	110	70	140
24	0	11	7	55	119	79	156
25	0	13	7	56	119	79	254
26	0	13	7	57	119	80	271
27	0	14	7	58	123	84	271
28	0	16	7	59	123	85	271
29	0	16	7	60	123	90	272
30	0	16	7	61	123	100	272
31	0	21	7	62	128	101	283

Data table for chapter 1, Figure 1.2b cont'd

Date	AEZ I	AEZ II	AEZ III	Date	AEZ I	AEZ II	AEZ III
63	128	105	283	94	253	321	605
64	128	111	284	95	253	340	641
65	134	111	285	96	267	353	647
66	134	116	285	97	282	369	650
67	134	121	289	98	297	369	663
68	134	124	294	99	297	382	670
69	150	125	297	100	297	395	679
70	190	128	297	101	297	407	684
71	196	131	303	102	309	427	690
72	196	134	312	103	309	438	704
73	196	138	313	104	324	440	706
74	210	138	317	105	324	442	721
75	220	143	336	106	324	458	741
76	220	149	391	107	324	470	744
77	220	157	391	108	324	482	745
78	220	167	391	109	324	496	751
79	220	180	397	110	336	509	751
80	222	180	408	111	336	513	787
81	227	195	425	112	336	520	788
82	227	208	445	113	348	524	793
83	227	225	457	114	348	528	828
84	227	239	476	115	348	544	862
85	230	256	490	116	348	552	895
86	233	270	507	117	363	564	925
87	233	274	513	118	363	575	928
88	234	282	514	119	384	587	945
89	237	282	526	120	402	600	960
90	237	286	542	121	402	609	976
91	243	291	557	122	402	614	992
92	243	295	565	123	417	619	1007
93	253	301	569	124	417	632	1010

Data table for chapter 1, Figure 1.2b cont'd

Date	AEZ I	AEZ II	AEZ III	Date	AEZ I	AEZ II	AEZ III
125	422	646	1027	158	483	856	1312
126	422	661	1092	159	483	858	1327
127	422	679	1117	160	483	860	1343
128	422	688	1122	161	483	861	1343
129	428	697	1123	162	483	861	1343
130	433	705	1125	163	487	861	1343
131	433	712	1132	164	487	861	1345
132	434	718	1133	165	487	861	1346
133	434	724	1133	166	487	862	1346
134	434	730	1156	167	491	862	1348
135	434	733	1162	168	491	862	1354
136	434	738	1169	169	502	862	1354
137	434	742	1169	170	502	862	1354
138	434	748	1179	171	502	862	1354
139	434	754	1180	172	502	862	1355
140	434	760	1180	173	502	863	1360
141	458	768	1204	174	502	863	1360
142	466	768	1220	175	502	863	1360
143	466	768	1232	176	502	863	1365
144	466	768	1237	177	502	863	1365
145	466	768	1237	178	502	863	1365
146	466	768	1237	179	502	863	1365
147	466	782	1240	180	502	863	1365
148	470	782	1240	181	502	863	1365
149	470	799	1248	182	502	864	1365
150	470	817	1260	183	502	865	1365
151	470	832	1280	184	502	865	1365
152	478	844	1290	185	502	867	1365
153	478	849	1290	186	502	867	1365
154	478	849	1300	187	502	871	1365
155	478	853	1300	188	502	871	1365
156	480	856	1302	189	502	875	1365
157	483	856	1312	190	502	875	1365

Data table for chapter 1, Figure 1.2b cont'd

Date	AEZ I	AEZ II	AEZ III	Date	AEZ I	AEZ II	AEZ III
191	502	875	1365	202	502	884	1377
192	502	875	1365	203	502	884	1377
193	502	876	1365	204	502	885	1377
194	502	876	1371	205	502	885	1377
195	502	876	1377	206	502	885	1377
196	502	876	1377	207	502	885	1377
197	502	878	1377	208	502	885	1377
198	502	878	1377	209	502	885	1382
199	502	881	1377	210	502	885	1387
200	502	881	1377	211	502	885	1392
201	502	882	1377	212	502	885	1392

Data table for chapter 1, Figure 1.3, 1.4, 1. 5

Treatment	Yield	Rainfall	Silt + clay	pH	N	C	CEC	P	Elevation	Curvature
	t ha^{-1}	mm	%		g kg^{-1}		mmolc kg^{-1}		m	
CF	1.4	563	74	5.6	2.6	33.2	46.7	1.7	553	-0.041
CF	2.1	563	42	5.6	1.2	15.8	25.3	1.4	556	0.000
CF	0.9	563	39	5.6	1.1	15.6	24.7	1.1	556	-0.033
CF	1.7	563	85	5.4	2.1	34.4	52.3	1.1	554	-0.025
CF	1.9	563	46	5.8	1.3	16.5	32.4	1.6	555	0.025
CF	0.2	589	46	5.8	1.1	14.2	27.5	1.1	561	0.016
CF	1.8	589	43	5.1	1.2	16.0	29.4	1.7	561	0.008
CF	1.6	589	24	5.5	0.7	7.2	12.3	-3.0	561	0.016
CF	0.8	589	34	5.9	0.8	10.2	23.4	-2.1	560	-0.008
CF	2.2	563	73	6.8	1.9	30.7	46.5	0.4	556	0.041
CF	1.8	573	50	5.8	1.6	23.4	36.4	2.1	539	0.033
CF	1.8	573	42	5.6	1.1	14.5	36.4	2.1	554	-0.016
CF	1.6	595	83	6.6	1.6	23.7	52.6	-0.4	559	-0.008
CF	2.1	599	43	6.7	1.8	23.2	38.8	-0.8	558	-0.033
CF	0.9	595	24	6.3	0.8	9.8	18.1	1.6	562	-0.008
CF	2.3	596	46	6.1	1.0	13.1	31.8	1.6	562	-0.016
CF	1.0	595	55	6.1	1.4	19.9	35.7	3.2	563	-0.033
CF	0.9	596	89	7.1	2.5	39.9	57.7	-0.9	562	-0.008
CF	1.5	566	71	6.6	1.7	30.2	46.2	1.2	563	0.000
CF	0.9	563	92	5.7	1.3	21.1	56.0	-0.7	540	0.000
CF	0.8	566	94	5.9	2.3	36.2	59.8	0.2	563	0.000
CF	1.5	590	50	6.6	1.1	13.4	33.1	1.7	563	0.000
CF	0.5	592	78	6.4	1.9	27.4	48.0	4.4	563	0.000
CF	1.5	591	70	6.2	.	.	51.1	3.6	563	0.000

Data table for chapter 1, Figure 1.3, 1.4, 1.5 cont'd

Treatment	Yield	Rainfall	Silt + clay	pH	N	C	CEC	P	Elevation	Curvature
	t ha^{-1}	mm	%		g kg^{-1}		mmolc kg^{-1}		m	
CF	1.3	590	46	6.3	0.9	13.1	27.2	1.1	550	-0.008
CF	1.6	595	68	6.6	1.4	19.6	28.7	-0.2	539	-0.025
CF	0.7	593	.	.	0.8	11.8	23.8	1.2	.	.
CF	2.0	559	36	.	1.0	14.6	21.0	1.2	564	0.033
CF	1.4	559	.	.	1.5	17.6	27.1	2.7	.	.
CF	0.5	559	33	6.2	.	.	23.8	0.8	536	0.000
CF	2.3	591	.	.	.	.	28.4	0.8	.	.
CF	1.6	591	35	5.4	0.9	12.7	27.2	-1.4	541	-0.008
CF	1.5	563	.	.	2.1	31.3	45.5	1.0	.	.
CF	2.1	595	.	.	1.1	16.0	22.5	0.4	.	.
CF	1.4	566	35	6.0	1.4	20.5	28.7	0.4	572	-0.025
CF	0.9	586	22	6.2	0.6	9.1	18.7	-1.8	568	-0.049
CF	1.8	586	.	.	1.3	17.2	29.7	1.7	.	.
CF	1.6	566	.	.	0.9	12.1	20.9	0.5	.	.
CF	1.8	566	.	.	1.4	20.6	28.7	2.3	.	.
CF	0.8	570	.	.	1.7	25.4	57.5	-0.6	.	.
CF	1.3	570	.	.	1.0	12.4	18.3	1.8	.	.
CF	1.3	566	.	.	1.3	18.7	29.4	1.1	.	.
CF	0.6	589	.	.	0.9	12.6	30.4	1.6	.	.
CF	0.7	589	32	6.6	1.1	14.3	26.9	-0.1	560	-0.016
CF	1.7	589	48	6.0	1.8	27.4	46.2	0.8	558	-0.008
CF	1.3	563	43	6.2	1.3	17.8	32.2	-0.1	556	0.008
CF	1.3	563	32	6.1	1.2	16.1	26.2	0.3	533	0.008
CF	2.0	566	88	5.9	1.8	26.1	55.6	-0.7	553	-0.058

Data table for chapter 1, Figure 1.3, 1.4, 1.5 cont'd

Treatment	Yield	Rainfall	Silt + clay	pH	N	C	CEC	P	Elevation	Curvature
	t ha^{-1}	mm	%		g kg^{-1}		mmolc kg^{-1}		m	
CF	1.8	563	41	6.0	1.3	18.0	30.9	-1.3	556	0.000
CF	2.0	563	.	.	2.4	36.5	63.6	-2.4	.	.
CF	2.0	566	.	.	0.9	13.3	20.7	0.9	.	.
CF	0.5	563	.	.	2.6	37.2	59.0	0.4	.	.
CF	0.7	490	11	6.0	0.7	10.0	16.4	2.4	563	0.000
CF	1.4	587	.	.	.	.	56.1	18.7	563	0.000
CF	0.8	582	.	.	.	.	96.9	32.3	555	0.016
CF	1.1	969	21	5.7	0.7	9.8	4.8	0.1	1129	0.008
CF	0.7	969	25	5.3	0.5	7.0	5.4	1.2	1130	0.049
CF	0.5	958	29	5.4	0.5	7.2	8.6	3.3	1120	0.033
CF	0.9	969	9	5.7	0.4	6.0	4.1	0.7	1134	0.016
CF	0.5	877	16	5.8	0.4	4.2	6.1	2.0	1086	0.033
CF	0.3	877	10	6.3	0.3	5.2	2.6	0.2	1112	-0.074
CF	0.4	874	9	5.7	0.3	3.7	3.7	1.3	1100	0.025
CF	0.7	812	26	5.5	0.8	11.4	11.8	0.1	1073	-0.033
CF	1.1	809	10	5.7	0.4	7.0	5.1	0.0	1129	0.074
CF	1.1	809	28	5.4	0.7	10.0	8.5	2.4	1117	0.016
CF	0.7	814	33	5.9	0.9	12.1	14.7	3.3	1116	0.033
CF	1.0	814	39	5.6	1.0	12.5	13.2	1.0	1064	0.000
CF	2.1	816	16	5.7	0.5	5.9	5.9	0.6	1082	0.000
CF	0.8	816	9	5.3	0.3	5.0	2.3	-1.2	1118	0.082
CF	1.6	816	11	5.7	0.5	6.0	5.1	-1.6	1049	0.025
CF	0.8	815	38	5.7	0.8	11.6	20.0	1.1	1070	0.107

Data table for chapter 1, Figure 1.3, 1.4, 1.5 cont'd

Treatment	Yield	Rainfall	Silt + clay	pH	N	C	CEC	P	Elevation	Curvature
	t ha^{-1}	mm	%		g kg^{-1}		mmolc kg^{-1}		m	
CF	0.8	793	15	5.7	0.4	5.8	5.7	-1.2	1131	-0.033
CF	1.5	793	21	5.5	0.4	4.5	5.7	0.4	1142	-0.074
CF	0.1	916	11	5.8	0.7	12.3	7.6	0.0	1142	0.041
CF	0.8	817	15	5.8	0.1	-0.5	6.1	0.5	1126	-0.082
CF	0.5	815	15	5.8	0.4	5.4	4.3	-0.5	1100	0.041
CF	1.2	818	.	.	.	.	105.4	34.5	1088	-0.082
CF	1.4	909	18	5.6	0.4	5.8	8.5	-2.1	1042	-0.041
CF	2.0	909	.	.	0.7	9.4	5.5	-0.7	1087	0.008
CF	1.0	909	19	5.7	0.4	6.9	5.2	-1.4	1101	0.016
CF	1.5	909	29	5.4	0.5	6.0	8.9	-0.3	1083	-0.041
CF	1.1	911	27	5.5	0.6	8.8	9.6	0.6	1130	0.000
CF	1.6	911	23	5.7	0.8	12.2	10.2	-0.7	1148	0.090
CF	0.8	918	20	6.2	0.4	5.6	6.6	-0.4	1118	-0.008
CF	1.4	909	23	6.9	0.3	3.8	8.1	1.7	1100	-0.025
CF	1.2	916	15	6.6	0.7	9.9	5.6	-1.2	1108	0.000
CF	1.1	903	24	7.3	0.8	12.1	27.0	1.8	1157	0.049
CF	0.8	905	30	6.9	0.5	8.2	10.3	1.6	1187	-0.041
CF	1.2	899	33	6.0	0.5	6.6	6.0	0.5	1213	-0.049
CF	0.7	904	36	6.1	0.3	4.1	4.5	-0.8	1129	-0.082
CF	0.7	917	37	7.1	0.4	4.7	11.8	0.6	1037	0.025
CF	0.3	915	23	5.8	0.4	5.8	6.1	1.0	1048	0.041
CF	0.6	919	27	5.9	0.4	6.6	16.0	2.1	1061	-0.066
CF	0.4	919	17	5.7	0.4	5.3	4.5	0.4	1048	-0.008

Data table for chapter 1, Figure 1.3, 1.4, 1.5 cont'd

Treatment	Yield	Rainfall	Silt + clay	pH	N	C	CEC	P	Elevation	Curvature
	t ha^{-1}	mm	%		g kg^{-1}		mmolc kg^{-1}		m	
CF	0.8	918	19	6.0	0.4	5.1	4.8	0.1	1077	-0.008
CF	0.7	917	18	6.0	0.3	3.7	5.4	1.2	1072	0.008
CF	1.1	917	18	4.9	0.3	3.8	8.6	3.3	1054	-0.008
CF	1.5	917	25	5.5	0.4	3.9	8.6	3.3	1070	0.041
CF	1.9	920	29	5.2	0.5	5.5	4.1	0.7	1068	-0.033
CF	2.1	910	25	5.5	0.9	13.6	4.1	0.7	1062	-0.008
CF	1.2	918	27	5.3	0.5	6.9	6.1	2.0	1074	-0.025
CF	0.7	766	20	6.1	0.6	7.8	6.1	2.0	1036	0.058
CF	1.5	710	30	5.9	1.3	21.0	2.6	0.2	1034	0.115
CF	0.5	724	34	5.6	1.3	21.5	1.8	-0.8	1032	-0.008
CF	1.1	724	39	6.0	0.8	11.7	3.7	1.3	1040	-0.016
CF	0.5	726	19	6.0	0.9	12.0	11.8	0.1	1064	0.058
CF	0.4	725	32	5.8	1.2	18.6	11.8	0.1	1034	-0.025
CF	1.8	727	31	6.1	1.0	16.4	5.1	0.0	1041	-0.041
CF	0.6	764	20	6.0	0.6	9.5	5.1	0.0	1033	0.025
CF	1.3	776	14	5.8	0.7	11.2	8.5	2.4	1037	0.033
CF	0.7	798	.	.	.	.	8.5	2.4	964	-0.049
CF	0.8	799	.	.	.	.	14.7	3.3	947	0.049
CF	1.5	795	21	5.7	0.5	8.2	14.7	3.3	975	0.066
CF	1.5	793	.	.	.	.	11.3	0.3	1032	0.131
CF	0.5	797	.	.	.	.	13.2	1.0	1018	-0.025
CF	1.4	794	.	.	.	.	13.2	1.0	964	0.016
CF	1.8	797	.	.	.	.	5.9	0.6	1013	-0.041
CF	0.6	795	22	5.7	0.3	3.9	5.9	0.6	1063	0.008

Data table for chapter 1, Figure 1.3, 1.4, 1.5 cont'd

Treatment	Yield	Rainfall	Silt + clay	pH	N	C	CEC	P	Elevation	Curvature
	t ha^{-1}	mm	%		g kg^{-1}		mmolc kg^{-1}		m	
CF	0.2	795	18	5.4	0.5	6.8	2.3	-1.2	1051	0.016
CF	1.4	795	32	5.3	1.0	15.6	2.3	-1.2	1067	0.041
CF	0.1	795	16	6.6	0.4	5.9	5.1	-1.6	1039	-0.066
CF	0.3	796	24	5.6	0.6	11.6	5.1	-1.6	1017	0.025
CF	1.1	793	19	5.9	0.9	11.7	20.0	1.1	653	0.033
CF	0.3	789	19	5.9	0.7	9.7	20.0	1.1	627	0.025
CF	0.9	793	21	5.8	0.6	8.7	11.3	0.1	654	-0.016
CF	1.4	689	19	6.6	0.6	8.3	7.9	-1.2	633	0.049
CF	1.7	689	16	6.7	0.8	13.2	10.6	-1.2	634	0.025
CF	1.6	695	39	6.0	0.7	11.9	17.4	0.4	627	-0.016
CF	0.4	691	23	6.0	0.6	7.4	14.4	0.4	701	-0.041
CF	0.3	696	.	.	.	.	7.6	0.0	698	-0.033
CF	0.9	696	.	.	.	.	7.6	0.0	698	-0.016
CF	1.5	695	33	5.9	0.7	9.4	18.1	0.5	696	-0.049
CF	0.8	689	49	5.3	1.1	19.6	20.6	0.5	627	0.033
CF	0.9	695	45	5.8	1.3	21.2	23.1	-0.5	693	0.033
CF	1.3	692	40	5.6	1.0	15.6	22.5	-0.5	698	0.049
CF	1.4	499	43	5.1	0.7	9.3	18.3	-2.1	608	0.000
CF	0.5	499	65	5.1	1.6	25.7	27.0	-2.1	611	-0.058
CF	0.9	499	34	5.3	0.7	9.4	12.8	-0.7	614	-0.025
CF	0.8	493	34	6.3	1.0	13.2	23.5	-0.7	615	0.000
CF	1.6	499	22	6.1	0.6	8.9	11.8	-1.4	616	-0.025
CF	1.6	491	33	5.8	1.0	17.2	16.1	-1.4	618	0.000

Data table for chapter 1, Figure 1.3, 1.4, 1.5 cont'd

Treatment	Yield	Rainfall	Silt + clay	pH	N	C	CEC	P	Elevation	Curvature
	t ha^{-1}	mm	%		g kg^{-1}		mmolc kg^{-1}		m	
CF	0.4	491	17	5.9	0.5	5.2	9.0	-0.3	622	-0.008
CF	0.5	499	21	5.9	0.6	7.0	8.3	-0.3	620	0.008
CF	0.8	499	13	6.0	0.3	3.5	8.1	0.6	623	0.033
CF	0.9	914	.	.	.	.	9.6	0.6	1077	-0.025
CF	1.2	912	.	.	.	.	10.2	-0.7	1115	0.041
CF	1.7	1399	29	5.3	0.7	11.7	10.7	0.1	1395	-0.016
CF	1.1	1399	26	5.2	1.4	26.8	14.7	0.2	1394	-0.008
CF	1.8	1363	77	6.4	0.9	11.8	9.0	0.3	1398	0.090
CF	1.6	1379	73	4.9	1.0	15.9	7.9	0.1	1374	-0.025
CF	1.6	1372	76	4.4	0.8	12.8	4.6	-0.9	1373	-0.016
CF	1.6	1385	32	4.8	0.9	13.8	11.2	-0.2	1366	-0.058
CF	0.1	1397	64	4.7	1.4	23.3	5.5	0.3	1387	0.033
CF	1.8	1365	62	4.8	0.8	10.9	13.8	0.2	1390	0.099
CF	0.2	1364	68	4.7	1.1	17.0	16.5	0.2	1394	-0.205
CF	0.9	1256	83	4.7	2.5	43.6	20.2	1.6	1427	0.066
CF	0.8	1356	50	4.8	1.0	15.7	11.3	-0.3	1418	-0.016
CF	1.5	1356	60	5.1	1.2	21.3	13.5	-0.3	1406	0.041
CF	1.5	1376	40	5.1	0.8	11.1	7.3	0.0	1382	0.107
CF	1.5	1382	65	4.8	1.1	18.5	25.0	0.0	1382	0.058
CF	2.2	1376	64	4.9	1.6	27.0	23.9	0.2	1383	0.041
CF	1.1	1396	43	5.4	0.8	12.5	8.4	-0.1	1398	-0.008
CF	1.7	1397	36	4.9	0.7	9.3	9.3	0.0	1390	-0.008
CF	1.0	1358	82	5.0	2.4	40.6	23.6	-0.4	1427	0.066
CF	1.7	1372	23	5.8	0.8	12.7	9.0	0.0	1395	-0.016

Data table for chapter 1, Figure 1.3, 1.4, 1.5 cont'd

Treatment	Yield	Rainfall	Silt + clay	pH	N	C	CEC	P	Elevation	Curvature
	t ha^{-1}	mm	%		g kg^{-1}		mmolc kg^{-1}		m	
CF	1.3	1375	27	5.1	0.6	9.3	6.3	-0.6	1395	-0.049
CF	2.1	1343	25	4.7	0.6	9.5	7.0	0.0	1409	0.025
TF	1.7	563	74	5.6	2.6	33.2	46.7	1.7	553	-0.041
TF	1.2	563	42	5.6	1.2	15.8	25.3	1.4	556	0.000
TF	0.0	563	39	5.6	1.1	15.6	24.7	1.1	556	-0.033
TF	1.7	563	85	5.4	2.1	34.4	52.3	1.1	554	-0.025
TF	0.0	563	46	5.8	1.3	16.5	32.4	1.6	555	0.025
TF	0.0	589	46	5.8	1.1	14.2	27.5	1.1	561	0.016
TF	0.0	589	43	5.1	1.2	16.0	29.4	1.7	561	0.008
TF	1.2	589	24	5.5	0.7	7.2	12.3	-3.0	561	0.016
TF	1.2	589	34	5.9	0.8	10.2	23.4	-2.1	560	-0.008
TF	1.6	563	73	6.8	1.9	30.7	46.5	0.4	556	0.041
TF	1.4	573	50	5.8	1.6	23.4	36.4	2.1	539	0.033
TF	2.0	573	42	5.6	1.1	14.5	36.4	2.1	554	-0.016
TF	1.2	595	83	6.6	1.6	23.7	52.6	-0.4	559	-0.008
TF	1.4	599	43	6.7	1.8	23.2	38.8	-0.8	558	-0.033
TF	0.9	595	24	6.3	0.8	9.8	18.1	1.6	562	-0.008
TF	0.0	596	46	6.1	1.0	13.1	31.8	1.6	562	-0.016
TF	0.4	595	55	6.1	1.4	19.9	35.7	3.2	563	-0.033
TF	0.0	596	89	7.1	2.5	39.9	57.7	-0.9	562	-0.008
TF	1.6	566	71	6.6	1.7	30.2	46.2	1.2	563	0.000
TF	0.2	563	92	5.7	1.3	21.1	56.0	-0.7	540	0.000
TF	1.7	566	94	5.9	2.3	36.2	59.8	0.2	563	0.000
TF	1.6	590	50	6.6	1.1	13.4	33.1	1.7	563	0.000

Data table for chapter 1, Figure 1.3, 1.4, 1.5 cont'd

Treatment	Yield	Rainfall	Silt + clay	pH	N	C	CEC	P	Elevation	Curvature
	t ha^{-1}	mm	%		g kg^{-1}		mmolc kg^{-1}		m	
TF	0.6	592	78	6.4	1.9	27.4	48.0	4.4	563	0.000
TF	0.8	591	70	6.2	.	.	51.1	3.6	563	0.000
TF	1.8	590	46	6.3	0.9	13.1	27.2	1.1	550	-0.008
TF	0.0	595	68	6.6	1.4	19.6	28.7	-0.2	539	-0.025
TF	0.0	593	.	.	0.8	11.8	23.8	1.2	.	.
TF	1.3	559	36	.	1.0	14.6	21.0	1.2	564	0.033
TF	1.3	559	.	.	1.5	17.6	27.1	2.7	.	.
TF	0.2	559	33	6.2	.	.	23.8	0.8	536	0.000
TF	0.0	591	.	.	.	.	28.4	0.8	.	.
TF	0.0	591	35	5.4	0.9	12.7	27.2	-1.4	541	-0.008
TF	0.0	563	.	.	2.1	31.3	45.5	1.0	.	.
TF	1.0	595	.	.	1.1	16.0	22.5	0.4	.	.
TF	1.5	566	35	6.0	1.4	20.5	28.7	0.4	572	-0.025
TF	0.6	586	22	6.2	0.6	9.1	18.7	-1.8	568	-0.049
TF	0.8	586	.	.	1.3	17.2	29.7	1.7	.	.
TF	1.5	566	.	.	0.9	12.1	20.9	0.5	.	.
TF	0.7	566	.	.	1.4	20.6	28.7	2.3	.	.
TF	0.9	570	.	.	1.7	25.4	57.5	-0.6	.	.
TF	0.5	570	.	.	1.0	12.4	18.3	1.8	.	.
TF	1.0	566	.	.	1.3	18.7	29.4	1.1	.	.
TF	0.0	589	.	.	0.9	12.6	30.4	1.6	.	.
TF	0.9	589	32	6.6	1.1	14.3	26.9	-0.1	560	-0.016
TF	0.8	589	48	6.0	1.8	27.4	46.2	0.8	558	-0.008

Data table for chapter 1, Figure 1.3, 1.4, 1.5 cont'd

Treatment	Yield	Rainfall	Silt + clay	pH	N	C	CEC	P	Elevation	Curvature
	t ha^{-1}	mm	%		g kg^{-1}		mmolc kg^{-1}		m	
TF	0.0	563	43	6.2	1.3	17.8	32.2	-0.1	556	0.008
TF	1.8	563	32	6.1	1.2	16.1	26.2	0.3	533	0.008
TF	1.9	566	88	5.9	1.8	26.1	55.6	-0.7	553	-0.058
TF	1.0	563	41	6.0	1.3	18.0	30.9	-1.3	556	0.000
TF	1.0	563	.	.	2.4	36.5	63.6	-2.4	.	.
TF	2.2	566	.	.	0.9	13.3	20.7	0.9	.	.
TF	0.0	563	.	.	2.6	37.2	59.0	0.4	.	.
TF	0.5	490	11	6.0	0.7	10.0	16.4	2.4	563	0.000
TF	1.7	587	.	.	.	.	56.1	18.7	563	0.000
TF	0.0	582	.	.	.	.	96.9	32.3	555	0.016
TF	1.0	969	21	5.7	0.7	9.8	4.8	0.1	1129	0.008
TF	0.7	969	25	5.3	0.5	7.0	5.4	1.2	1130	0.049
TF	0.5	958	29	5.4	0.5	7.2	8.6	3.3	1120	0.033
TF	0.0	969	9	5.7	0.4	6.0	4.1	0.7	1134	0.016
TF	1.2	877	16	5.8	0.4	4.2	6.1	2.0	1086	0.033
TF	1.6	877	10	6.3	0.3	5.2	2.6	0.2	1112	-0.074
TF	0.6	874	9	5.7	0.3	3.7	3.7	1.3	1100	0.025
TF	0.1	812	26	5.5	0.8	11.4	11.8	0.1	1073	-0.033
TF	0.0	809	10	5.7	0.4	7.0	5.1	0.0	1129	0.074
TF	1.5	809	28	5.4	0.7	10.0	8.5	2.4	1117	0.016
TF	0.0	814	33	5.9	0.9	12.1	14.7	3.3	1116	0.033
TF	0.8	814	39	5.6	1.0	12.5	13.2	1.0	1064	0.000
TF	0.9	816	16	5.7	0.5	5.9	5.9	0.6	1082	0.000
TF	0.5	816	9	5.3	0.3	5.0	2.3	-1.2	1118	0.082

Data table for chapter 1, Figure 1.3, 1.4, 1.5 cont'd

Treatment	Yield	Rainfall	Silt + clay	pH	N	C	CEC	P	Elevation	Curvature
	t ha^{-1}	mm	%		g kg^{-1}		mmolc kg^{-1}		m	
TF	0.0	816	11	5.7	0.5	6.0	5.1	-1.6	1049	0.025
TF	0.0	815	38	5.7	0.8	11.6	20.0	1.1	1070	0.107
TF	0.3	793	15	5.7	0.4	5.8	5.7	-1.2	1131	-0.033
TF	0.7	793	21	5.5	0.4	4.5	5.7	0.4	1142	-0.074
TF	1.4	916	11	5.8	0.7	12.3	7.6	0.0	1142	0.041
TF	2.2	817	15	5.8	0.1	-0.5	6.1	0.5	1126	-0.082
TF	1.0	815	15	5.8	0.4	5.4	4.3	-0.5	1100	0.041
TF	1.3	818	.	.	.	.	105.4	34.5	1088	-0.082
TF	0.7	909	18	5.6	0.4	5.8	8.5	-2.1	1042	-0.041
TF	1.1	909	.	.	0.7	9.4	5.5	-0.7	1087	0.008
TF	1.5	909	19	5.7	0.4	6.9	5.2	-1.4	1101	0.016
TF	0.4	909	29	5.4	0.5	6.0	8.9	-0.3	1083	-0.041
TF	1.5	911	27	5.5	0.6	8.8	9.6	0.6	1130	0.000
TF	0.7	911	23	5.7	0.8	12.2	10.2	-0.7	1148	0.090
TF	0.5	918	20	6.2	0.4	5.6	6.6	-0.4	1118	-0.008
TF	0.5	909	23	6.9	0.3	3.8	8.1	1.7	1100	-0.025
TF	0.5	916	15	6.6	0.7	9.9	5.6	-1.2	1108	0.000
TF	1.5	903	24	7.3	0.8	12.1	27.0	1.8	1157	0.049
TF	2.2	905	30	6.9	0.5	8.2	10.3	1.6	1187	-0.041
TF	1.3	899	33	6.0	0.5	6.6	6.0	0.5	1213	-0.049
TF	0.8	904	36	6.1	0.3	4.1	4.5	-0.8	1129	-0.082
TF	0.5	917	37	7.1	0.4	4.7	11.8	0.6	1037	0.025
TF	1.8	915	23	5.8	0.4	5.8	6.1	1.0	1048	0.041
TF	1.3	919	27	5.9	0.4	6.6	16.0	2.1	1061	-0.066

Data table for chapter 1, Figure 1.3, 1.4, 1.5 cont'd

Treatment	Yield	Rainfall	Silt + clay	pH	N	C	CEC	P	Elevation	Curvature
	t ha^{-1}	mm	%		g kg^{-1}		mmolc kg^{-1}		m	
TF	1.5	919	17	5.7	0.4	5.3	4.5	0.4	1048	-0.008
TF	0.5	918	19	6.0	0.4	5.1	4.8	0.1	1077	-0.008
TF	1.1	917	18	6.0	0.3	3.7	5.4	1.2	1072	0.008
TF	1.1	917	18	4.9	0.3	3.8	8.6	3.3	1054	-0.008
TF	1.0	917	25	5.5	0.4	3.9	8.6	3.3	1070	0.041
TF	1.0	920	29	5.2	0.5	5.5	4.1	0.7	1068	-0.033
TF	0.7	910	25	5.5	0.9	13.6	4.1	0.7	1062	-0.008
TF	0.6	918	27	5.3	0.5	6.9	6.1	2.0	1074	-0.025
TF	0.3	766	20	6.1	0.6	7.8	6.1	2.0	1036	0.058
TF	0.5	710	30	5.9	1.3	21.0	2.6	0.2	1034	0.115
TF	0.5	724	34	5.6	1.3	21.5	1.8	-0.8	1032	-0.008
TF	0.8	724	39	6.0	0.8	11.7	3.7	1.3	1040	-0.016
TF	0.0	726	19	6.0	0.9	12.0	11.8	0.1	1064	0.058
TF	1.3	725	32	5.8	1.2	18.6	11.8	0.1	1034	-0.025
TF	0.9	727	31	6.1	1.0	16.4	5.1	0.0	1041	-0.041
TF	1.8	764	20	6.0	0.6	9.5	5.1	0.0	1033	0.025
TF	0.8	776	14	5.8	0.7	11.2	8.5	2.4	1037	0.033
TF	0.7	798	.	.	.	.	8.5	2.4	964	-0.049
TF	2.1	799	.	.	.	.	14.7	3.3	947	0.049
TF	0.0	795	21	5.7	0.5	8.2	14.7	3.3	975	0.066
TF	0.0	793	.	.	.	.	11.3	0.3	1032	0.131
TF	0.4	797	.	.	.	.	13.2	1.0	1018	-0.025
TF	0.0	794	.	.	.	.	13.2	1.0	964	0.016

Data table for chapter 1, Figure 1.3, 1.4, 1.5 cont'd

Treatment	Yield	Rainfall	Silt + clay	pH	N	C	CEC	P	Elevation	Curvature
	t ha^{-1}	mm	%		g kg^{-1}		mmolc kg^{-1}		m	
TF	1.3	797	.	.	.	.	5.9	0.6	1013	-0.041
TF	1.4	795	22	5.7	0.3	3.9	5.9	0.6	1063	0.008
TF	0.2	795	18	5.4	0.5	6.8	2.3	-1.2	1051	0.016
TF	0.0	795	32	5.3	1.0	15.6	2.3	-1.2	1067	0.041
TF	1.0	795	16	6.6	0.4	5.9	5.1	-1.6	1039	-0.066
TF	1.2	796	24	5.6	0.6	11.6	5.1	-1.6	1017	0.025
TF	1.4	793	19	5.9	0.9	11.7	20.0	1.1	653	0.033
TF	0.3	789	19	5.9	0.7	9.7	20.0	1.1	627	0.025
TF	1.3	793	21	5.8	0.6	8.7	11.3	0.1	654	-0.016
TF	1.0	689	19	6.6	0.6	8.3	7.9	-1.2	633	0.049
TF	0.8	689	16	6.7	0.8	13.2	10.6	-1.2	634	0.025
TF	0.0	695	39	6.0	0.7	11.9	17.4	0.4	627	-0.016
TF	1.1	691	23	6.0	0.6	7.4	14.4	0.4	701	-0.041
TF	1.5	696	.	.	.	.	7.6	0.0	698	-0.033
TF	0.5	696	.	.	.	.	7.6	0.0	698	-0.016
TF	0.6	695	33	5.9	0.7	9.4	18.1	0.5	696	-0.049
TF	0.8	689	49	5.3	1.1	19.6	20.6	0.5	627	0.033
TF	1.2	695	45	5.8	1.3	21.2	23.1	-0.5	693	0.033
TF	0.6	692	40	5.6	1.0	15.6	22.5	-0.5	698	0.049
TF	0.8	499	43	5.1	0.7	9.3	18.3	-2.1	608	0.000
TF	0.9	499	65	5.1	1.6	25.7	27.0	-2.1	611	-0.058
TF	0.3	499	34	5.3	0.7	9.4	12.8	-0.7	614	-0.025
TF	0.6	493	34	6.3	1.0	13.2	23.5	-0.7	615	0.000

Data table for chapter 1, Figure 1.3, 1.4, 1.5 cont'd

Treatment	Yield	Rainfall	Silt + clay	pH	N	C	CEC	P	Elevation	Curvature
	t ha^{-1}	mm	%		g kg^{-1}		mmolc kg^{-1}		m	
TF	0.9	499	22	6.1	0.6	8.9	11.8	-1.4	616	-0.025
TF	0.8	491	33	5.8	1.0	17.2	16.1	-1.4	618	0.000
TF	0.4	491	17	5.9	0.5	5.2	9.0	-0.3	622	-0.008
TF	0.9	499	21	5.9	0.6	7.0	8.3	-0.3	620	0.008
TF	0.9	499	13	6.0	0.3	3.5	8.1	0.6	623	0.033
TF	0.8	914	.	.	.	.	9.6	0.6	1077	-0.025
TF	0.0	912	.	.	.	.	10.2	-0.7	1115	0.041
TF	2.0	1399	29	5.3	0.7	11.7	10.7	0.1	1395	-0.016
TF	1.1	1399	26	5.2	1.4	26.8	14.7	0.2	1394	-0.008
TF	1.4	1363	77	6.4	0.9	11.8	9.0	0.3	1398	0.090
TF	1.6	1379	73	4.9	1.0	15.9	7.9	0.1	1374	-0.025
TF	2.0	1372	76	4.4	0.8	12.8	4.6	-0.9	1373	-0.016
TF	2.2	1385	32	4.8	0.9	13.8	11.2	-0.2	1366	-0.058
TF	1.3	1397	64	4.7	1.4	23.3	5.5	0.3	1387	0.033
TF	0.9	1365	62	4.8	0.8	10.9	13.8	0.2	1390	0.099
TF	1.9	1364	68	4.7	1.1	17.0	16.5	0.2	1394	-0.205
TF	0.6	1256	83	4.7	2.5	43.6	20.2	1.6	1427	0.066
TF	0.0	1356	50	4.8	1.0	15.7	11.3	-0.3	1418	-0.016
TF	0.0	1356	60	5.1	1.2	21.3	13.5	-0.3	1406	0.041

Data table for chapter 1, Figure 1.3, 1.4, 1.5 cont'd

Treatment	Yield	Rainfall	Silt + clay	pH	N	C	CEC	P	Elevation	Curvature
	t ha^{-1}	mm	%		g kg^{-1}		mmolc kg^{-1}		m	
TF	0.6	1376	40	5.1	0.8	11.1	7.3	0.0	1382	0.107
TF	1.6	1382	65	4.8	1.1	18.5	25.0	0.0	1382	0.058
TF	2.5	1376	64	4.9	1.6	27.0	23.9	0.2	1383	0.041
TF	0.3	1396	43	5.4	0.8	12.5	8.4	-0.1	1398	-0.008
TF	2.7	1397	36	4.9	0.7	9.3	9.3	0.0	1390	-0.008
TF	1.5	1358	82	5.0	2.4	40.6	23.6	-0.4	1427	0.066
TF	2.2	1372	23	5.8	0.8	12.7	9.0	0.0	1395	-0.016
TF	1.8	1375	27	5.1	0.6	9.3	6.3	-0.6	1395	-0.049
TF	2.4	1343	25	4.7	0.6	9.5	7.0	0.0	1409	0.025

Data table for chapter 1, Figure 1.6

	AEZ I		AEZ II		AEZ III	
Slope position	grain yield (t ha-1)	Stdev	grain yield (t ha-1)	Stdev	grain yield (t ha-1)	Stdev
Ridge	0.5	0.62	0.9	0.48	1.4	0.65
Upper slope	0.8	0.69	1.1	0.43	1.9	0.69
Lower slope	0.9	0.46	0.9	0.55	2.0	0.39
Flat slope	1.1	0.63	0.9	0.63	1.3	0.55
Valley	1.3	0.59	0.9	0.57	1.2	0.74

Data table for chapter 1, Figure 1.7a

Planting date AEZ I	TF yield (t ha-1)	Planting date AEZ II	TF yield (t ha-1)	Planting date AEZ III	TF yield (t ha-1)
11-Nov	0.9	13-Oct	1.0	5-Dec	2.4
18-Nov	1.7	24-Oct	1.5	6-Dec	1.4
18-Nov	1.7	24-Oct	1.5	6-Dec	0.9
19-Nov	1.6	24-Oct	1.1	6-Dec	1.6
20-Nov	1.2	31-Oct	1.4	6-Dec	2.5
20-Nov	1.2	31-Oct	2.2	6-Dec	0.8
20-Nov	0.4	31-Oct	1.3	6-Dec	0.3
20-Nov	0.2	4-Nov	0.5	6-Dec	2.7
21-Nov	1.0	4-Nov	0.5	6-Dec	2.2
22-Nov	1.2	4-Nov	1.2	6-Dec	1.8
22-Nov	1.2	4-Nov	1.6	8-Dec	2.2
22-Nov	2.0	4-Nov	0.1	8-Dec	0.6
22-Nov	1.5	11-Nov	0.6	9-Dec	1.6
23-Nov	0.9	13-Nov	0.5	9-Dec	2.0
23-Nov	0.8	13-Nov	1.1	12-Dec	1.3
23-Nov	1.9	13-Nov	0.7	13-Dec	1.9
23-Nov	2.2	13-Nov	0.5	13-Dec	1.5
24-Nov	0.2	13-Nov	0.9		
24-Nov	0.7	13-Nov	0.8		
24-Nov	1.0	14-Nov	0.8		
25-Nov	1.4	14-Nov	0.7		
25-Nov	1.7	14-Nov	1.3		
25-Nov	1.3	14-Nov	0.7		
25-Nov	1.0	14-Nov	1.5		
26-Nov	1.6	14-Nov	0.3		
26-Nov	0.8	14-Nov	1.3		
26-Nov	1.3	14-Nov	0.8		
28-Nov	0.6	14-Nov	0.6		
28-Nov	1.8	16-Nov	1.5		
28-Nov	0.8	16-Nov	1.8		
28-Nov	1.5	16-Nov	0.8		
30-Nov	1.4	16-Nov	0.7		
30-Nov	1.6	17-Nov	0.3		
30-Nov	0.6	17-Nov	1.3		
30-Nov	0.5	17-Nov	1.0		

Data table for chapter 1, Figure 1.7a cont'd

Planting date AEZ I	TF yield (t ha-1)	Planting date AEZ II	TF yield (t ha-1)	Planting date AEZ III	TF yield (t ha-1)
1-Dec	1.0	17-Nov	0.6		
2-Dec	0.9	18-Nov	0.6		
6-Dec	0.5	18-Nov	0.8		
7-Dec	1.7	18-Nov	0.9		
19-Dec	1.8	18-Nov	1.0		
		16-Nov	0.3		
		16-Nov	0.5		
		16-Nov	1.3		
		16-Nov	0.5		
		16-Nov	1.2		
		17-Nov	1.8		
		17-Nov	0.9		
		18-Nov	1.0		
		18-Nov	1.1		
		18-Nov	1.0		
		18-Nov	0.7		
		19-Nov	2.2		
		19-Nov	1.4		
		19-Nov	1.4		
		20-Nov	1.5		
		20-Nov	0.5		
		23-Nov	1.4		
		23-Nov	0.3		
		23-Nov	1.3		
		23-Nov	1.1		
		24-Nov	0.2		
		24-Nov	1.0		
		24-Nov	1.2		
		24-Nov	0.5		
		25-Nov	0.5		
		26-Nov	0.4		
		26-Nov	0.8		
		26-Nov	1.5		
		27-Nov	2.1		
		27-Nov	0.4		
		29-Nov	1.0		

Data table for chapter 1, Figure 1.7a cont'd

Planting date AEZ I	TF yield (t ha-1)	Planting date AEZ II	TF yield (t ha-1)	Planting date AEZ III	TF yield (t ha-1)
		3-Dec	2.0		
		5-Dec	2.0		
		10-Dec	1.1		
		11-Dec	0.6		
		15-Dec	0.8		
		18-Dec	0.7		
		20-Dec	0.9		
		20-Dec	0.4		
		21-Dec	0.3		
		21-Dec	0.6		
		21-Dec	0.9		

Data table for chapter 1, Figure 1.7b

Planting date AEZ I	CF yield (t ha-1)	Planting date AEZ II	CF yield (t ha-1)	Planting date AEZ III	CF yield (t ha-1)
11-Nov	1.5	8-Nov	0.8	12-Nov	1.2
11-Nov	0.8	11-Nov	1.4	15-Nov	0.9
11-Nov	1.6	11-Nov	0.7	18-Nov	0.5
12-Nov	0.7	11-Nov	0.3	18-Nov	1.6
13-Nov	2.3	12-Nov	1.8	18-Nov	1.6
14-Nov	2.3	13-Nov	1.1	22-Nov	0.5
14-Nov	2.0	14-Nov	0.5	23-Nov	1.4
14-Nov	1.4	14-Nov	0.4	24-Nov	0.8
14-Nov	0.5	15-Nov	0.8	29-Nov	0.4
18-Nov	1.5	15-Nov	1.9	1-Dec	1.6
18-Nov	0.5	15-Nov	2.1	2-Dec	0.8
18-Nov	1.5	15-Nov	1.2	3-Dec	2.1
18-Nov	1.3	15-Nov	1.3	3-Dec	0.9
20-Nov	0.9	15-Nov	0.8	4-Dec	1.1
28-Nov	0.8	17-Nov	1.5	5-Dec	0.2
29-Nov	1.6	24-Nov	0.1	6-Dec	0.8
1-Dec	1.8	24-Nov	1.2	6-Dec	0.9
1-Dec	1.8	24-Nov	1.4	6-Dec	1.5
1-Dec	2.1	24-Nov	2.0	7-Dec	1.5
2-Dec	1.4	24-Nov	1.6	7-Dec	1.7
2-Dec	0.8	24-Nov	1.4	8-Dec	1.7
2-Dec	2.2	24-Nov	1.2	9-Dec	1.7
3-Dec	2.1	25-Nov	2.0	9-Dec	1.1
3-Dec	1.9	25-Nov	0.5	10-Dec	0.1
3-Dec	1.6	25-Nov	1.1	11-Dec	1.5
3-Dec	0.9	25-Nov	1.5	11-Dec	2.2
3-Dec	1.5	25-Nov	0.5	12-Dec	1.0
4-Dec	0.2	25-Nov	1.0	13-Dec	1.6
4-Dec	1.8	25-Nov	1.1	14-Dec	1.8
4-Dec	0.9	25-Nov	0.7	12-Dec	1.8
4-Dec	1.6	25-Nov	1.8	13-Dec	1.3
5-Dec	0.9	26-Nov	1.0	14-Dec	1.6
5-Dec	1.8	26-Nov	1.6		
6-Dec	1.4	26-Nov	0.8		
7-Dec	1.7	26-Nov	0.8		

Data table for chapter 1, Figure 1.7b cont'd

Planting date AEZ I	CF yield (t ha-1)	Planting date AEZ II	CF yield (t ha-1)	Planting date AEZ III	CF yield (t ha-1)
10-Dec	1.6	26-Nov	1.5		
10-Dec	1.0	26-Nov	0.8		
10-Dec	1.8	26-Nov	1.2		
12-Dec	2.1	26-Nov	0.5		
15-Dec	0.9	26-Nov	0.4		
		27-Nov	0.7		
		27-Nov	0.8		
		27-Nov	0.8		
		27-Nov	0.7		
		27-Nov	1.1		
		27-Nov	1.5		
		27-Nov	1.1		
		27-Nov	0.1		
		27-Nov	0.3		
		29-Nov	1.1		
		29-Nov	1.5		
		29-Nov	0.5		
		29-Nov	1.8		
		30-Nov	1.4		
		Nov-31	2.0		
		Nov-31	1.5		
		Nov-31	1.7		
		Nov-31	1.6		
		1-Dec	0.8		
		1-Dec	1.4		
		2-Dec	0.7		
		2-Dec	1.3		
		2-Dec	0.7		
		2-Dec	0.4		
		2-Dec	0.3		
		2-Dec	0.9		
		2-Dec	1.7		
		2-Dec	1.3		
		4-Dec	2.0		
		5-Dec	1.3		
		5-Dec	1.3		

Data table for chapter 1, Figure 1.7a cont'd

Planting date AEZ I	TF yield (t ha-1)	Planting date AEZ II	TF yield (t ha-1)	Planting date AEZ III	TF yield (t ha-1)
		5-Dec	0.6		
		6-Dec	1.3		
		6-Dec	0.5		
		6-Dec	0.3		
		6-Dec	1.5		
		7-Dec	0.7		
		8-Dec	2.1		
		9-Dec	0.8		
		9-Dec	0.7		
		13-Dec	0.6		
		14-Dec	0.9		
		16-Dec	0.4		
		26-Dec	0.7		
		31-Dec	0.9		

Data table for chapter 2, Figure 2.2

Grain yield (t/ha)	pH	Grain yield (t/ha)	pH	Grain yield (t/ha)	pH
1.4	5.8	6.5	5.8	1.6	6.1
2.6	5.9	3.2	5.7	3.8	5.9
1.5	4.8	6.3	5.3	6.7	4.7
1.7	5.6	2.1	5.4	4.2	5.6
2.1	6.8	5.0	5.7	6.3	5.6
1.5	6.6	4.3	5.8	6.7	5.7
6.4	4.7	3.7	6.3	2.7	5.8
2.7	4.5	3.5	5.7	6.7	5.5
1.2	4.8	3.7	5.5	5.3	5.6
1.3	6.0	3.1	5.7	2.8	5.7
1.4	6.2	6.4	5.4	4.0	4.8
1.6	6.1	2.2	5.9	2.2	5.1
2.5	5.9	6.9	5.6	1.6	6.2
1.5	5.7	6.4	5.7	4.5	5.1
2.0	6.0	6.1	5.3	1.5	6.9
4.7	5.8	5.7	5.7	5.3	6.6
1.3	6.0	6.3	5.7	3.4	7.3
4.0	6.0	1.8	5.7	2.6	4.8
3.4	6.4	6.6	5.5	6.3	5.0
2.1	6.0	2.6	5.8	4.3	6.0
6.6	5.8	3.6	5.7	3.3	6.1
3.9	4.7	0.2	5.8	2.5	6.0
2.3	5.8	1.7	6.1	3.5	5.8
3.2	6.1	2.8	5.9	3.6	5.9
2.6	7.1	6.7	6.0	1.3	5.0
1.9	5.8	3.2	5.9	2.9	5.5
5.0	5.9	1.6	4.9	4.1	5.2
2.1	6.0	4.0	6.1	4.4	5.5
3.4	6.0	3.6	5.9	2.3	5.3
2.3	5.8	2.8	5.6		

Data table for chapter 2, Figure 2.2 b, c & d.

Grain yield (t/ha)	Silt+ clay %	N g kg^{-1}	C g kg^{-1}
7.0	18.1	0.70	11.68
	31.5	1.36	26.80
5.5	15.5	0.59	9.24
4.8	24.3	0.87	11.78
6.5	19.1	1.05	15.88
6.8	18.8	0.78	12.82
5.7	22.7	0.89	13.80
6.4	21.2	1.36	23.32
6.7	18.9	0.80	10.90
6.2	15.7	1.11	17.01
6.8	26.5	2.50	43.60
5.6	24.6	0.99	16.30
6.4	39.2	1.20	21.27
6.8	23.2	0.77	11.08
5.6		1.15	18.52
7.0	24.6	1.64	26.97
4.2		0.72	11.94
		0.83	12.48
6.6	32.5	0.73	14.08
	48.7	0.67	9.29
6.5	45.4	2.43	40.65
5.7	40.0	0.81	12.73
7.4	43.3	0.60	9.28
		0.57	9.46

Data table for chapter 2, Figure 2.3a

Grain yield (t ha^{-1})	Aspect
1.7	0.915
1.1	-0.355
	0.900
1.8	0.380
1.6	0.310
1.6	0.993
1.6	-0.997
0.1	-0.646
1.8	0.992
0.2	-0.951
0.9	-0.857
0.8	-0.503
1.5	-0.934
1.5	0.673
1.5	-0.998
2.2	0.624
	-0.291
1.1	-0.448
	-0.951
1.7	-0.951
1.0	-0.857
1.7	1.000
1.3	-0.647
2.1	0.840

Data table for chapter 2, Figure 2.3b

Grain yield (t ha^{-1})	Slope gradient
6.9	0.6159
0.7	0.4944
	0.3785
2.7	1.9360
1.3	0.2903
5.1	0.5879
4.0	2.5901
1.6	0.4106
3.9	3.7688
2.6	2.3014
1.4	2.6748
2.9	3.9427
3.7	2.0967
1.4	4.0090
4.6	4.3543
5.2	3.1036
0.2	1.1205
1.4	0.1298
	2.0521
2.7	2.0521
1.3	2.6748
1.8	0.3895
0.4	0.4681
0.5	1.3046

Data table for chapter 2, Figure 2.3c & d

Grain yield (t ha^{-1})	Rainfall, mm	Elevation, m
1.2	969.2	1117
4.2	969.2	1129
	969.2	1130
1.4	969.2	1130
1.7	957.7	1120
4.4	969.2	1134
1.5	876.8	1086
1.1	876.8	1112
0.4	870	1100
	874	1100
2.1	812	1073
1.6	808.5	1129
	806.8	1081
2.8	809.2	1117
3.4	813.5	1116
1.0	811	1042
3.2	813.5	1064
6.2	816.1	1082
2.7	816.1	1118
4.4	816.1	1049
2.3	815	1070
	711	1111
2.3	792.7	1139
1.9	792.7	1131
6.8		1142
4.6	915.9	1142
6.0	817	1126
4.2	814.6	1100
3.7	818	1088
5.8	909.2	1042
3.8	909.2	1087
6.8	909.2	1101

Data table for chapter 2, Figure 2.3 c & d cont'd

Grain yield (t ha^{-1})	Rainfall, mm	Elevation, m
2.2	909.2	1083
3.8	911.3	1130
6.9	809.2	1148
2.7	917.5	1118
6.8	909.2	1100
6.5	915.9	1108
4.9	903.2	1157
5.8	905	1187
3.5	899	1213
1.4	904	1129
4.1	916.7	1037
3.5	915	1048
	916	1045
1.8	919	1061
4.3	919	1048
3.9	917.5	1077
2.4	916.7	1072
3.3	916.7	1054
4.4	916.7	1070
6.1	920	1068
4.7	910	1062
3.8	918	1074
3.6	765.5	1036
2.2	769.3	1032
1.5	709.9	1034
6.3	723.7	1032
3.9	723.7	1040
3.7	725.6	1064
2.6	725	1034
2.7	727.3	1041
1.6	763.8	1033

Data table for chapter 2, Figure 2.3 c & d cont'd

Grain yield (t ha^{-1})	Rainfall, mm	Elevation, m
3.8	798	964
3.3	798.7	947
6.0	795.4	975
4.7	793	1032
6.8	796.9	1018
1.8	794	964
6.8	796.8	1013
3.0	795.2	1063
5.1	795.1	1047
1.9	794.5	1051
3.3	795.1	1067
3.1	795.4	1039
2.5	795.6	1036
1.5	796	1017
2.7	792.7	653
3.2	789	627
3.8	792.7	654
2.4	689	633
2.9	689	634
4.5	695.4	627
1.7	691	701
1.7	696.2	698
4.5	696.2	698
2.5	694.5	696
3.5	689	627
2.9	695.4	693
4.0	691.7	698
4.7	914	1077
1.1	912.2	1115
	792.7	654
3.9	775.6	1037

Data table for chapter 3, Figure 3.1a

	Basin		Row	
Year	Soil C (g kg^{-1})	Stderr	Soil C (g kg^{-1})	Stderr
2	11.1	0.9	10.3	1.0
4	12.2	1.0	11.1	1.2
6	13.9	1.3	12.9	1.5
8	10.0	1.7	10.8	2.2
10	10.3	1.5	9.4	1.5

Data table for chapter 3, Figure 3.1b

	Basin		Row	
Year	Soil N (g kg^{-1})	Stderr	Soil N (g kg^{-1})	Stderr
2	0.9	0.1	0.8	0.1
4	1.0	0.1	0.9	0.1
6	1.1	0.1	1.0	0.1
8	0.9	0.2	0.9	0.2
10	0.8	0.1	0.7	0.1

Data table for chapter 3, Figure 3.1c & d

Years	C (%)	Stdev	N (%)	Stdev
2	13.4	9.0	15.6	8.0
4	23.5	19.8	20.6	13.2
6	15.8	11.2	21.3	10.4
8	11.8	7.4	13.8	6.9
10	10.1	2.7	14.6	3.3

Data table for chapter 3, Figure 3.2a

	Basin		Row	
Years	mg CO_2-C g^{-1} soil day^{-1}	Stderr	mg CO_2-C g^{-1} soil day^{-1}	Stderr
2	39.2	7.41	79.4	44.27
4	84.6	16.71	68.2	5.94
6	92.3	23.18	51.9	18.35
8	122.2	34.03	92.1	59.17
10	120.4	19.48	48.5	19.25

Data table for chapter 3, Figure 3.2b

	Basin		Row	
Years	mg N g^{-1} soil day^{-1}	Stderr	mg N g^{-1} soil day^{-1}	Stderr
2	0.7	0.27	1.1	0.43
4	1.5	0.56	0.9	0.35
6	2.8	1.05	1.4	0.55
8	1.6	0.62	1.3	0.49
10	1.6	0.60	1.7	0.66

Data table for chapter 3, Figure 3.2c

	Basin		Row	
Years	mg CO_2-C g^{-1} C day^{-1}	Stderr	mg CO_2-C g^{-1} C day^{-1}	Stderr
2	3.9	0.92	5.7	3.32
4	8.9	2.69	6.8	0.81
6	7.6	2.43	2.9	1.66
8	10.9	1.99	0.4	5.06
10	10.7	2.06	3.7	1.16

Data table for chapter 3, Figure 3.2c

	Basin		Row	
Years	mg N g-1 N day^{-1}	Stderr	mg N g^{-1} N day^{-1}	Stderr
2	0.8	0.30	1.4	0.54
4	1.5	0.56	0.9	0.35
6	2.5	0.95	1.6	0.61
8	1.6	0.62	1.4	0.54
10	2.3	0.86	2.9	1.10

Data table for chapter 3, Figure 3.3a, 3b, & 3c

	Basin Soil organic C (mg C g^{-1} soil)					
Year	Free light	Stderr	Intra-aggregate	Stderr	Organo mineral	Stderr
2	0.11	0.01	0.04	0.00	9.20	0.95
4	0.19	0.02	0.08	0.01	6.63	1.24
6	0.23	0.03	0.04	0.01	7.71	1.38
8	0.12	0.17	0.03	0.00	3.59	0.18
10	0.18	0.02	0.05	0.01	5.97	0.39

Data table for chapter 3, Figure 3.3a, 3b, & 3c

	Row Soil organic C (mg C g^{-1} soil)					
Year	Free light	Stderr	Intra-aggregate	Stderr	Organo mineral	Stderr
2	0.15	0.03	0.04	0.01	9.45	1.43
4	0.16	0.02	0.04	0.00	7.23	1.45
6	0.12	0.02	0.04	0.01	6.20	1.39
8	0.08	0.00	0.01	0.01	3.65	0.33
10	0.13	0.01	0.04	0.00	3.97	0.76

Data table for chapter 3, Figure 3.4a, 4b, & 4c

	Basin Soil N (mg N g^{-1} soil)					
Year	Free light	Stderr	Intra-aggregate	Stderr	Organo mineral	Stderr
2	0.006	0.001	0.002	0.000	0.733	0.050
4	0.010	0.001	0.004	0.001	0.545	0.102
6	0.012	0.001	0.002	0.000	0.575	0.089
8	0.008	0.001	0.002	0.000	0.294	0.016
10	0.010	0.001	0.003	0.000	0.451	0.031

Data table for chapter 3, Figure 3.4a, 4b, & 4c

	Row Soil N (mg N g^{-1} soil)					
Year	Free light	Stderr	Intra-aggregate	Stderr	Organo mineral	Stderr
2	0.007	0.001	0.002	0.000	0.813	0.088
4	0.008	0.001	0.002	0.000	0.575	0.115
6	0.007	0.001	0.002	0.000	0.459	0.092
8	0.005	0.000	0.002	0.000	0.286	0.025
10	0.007	0.001	0.002	0.000	0.285	0.055